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The effect of drought on the water balance and yield of the potato crop in Belize

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Dedicated to my daughter

Chloe

Abstract

The intra- and inter-annual variability in key water balance components increases the vulnerability of Belize to drought events that can have significant impacts on its agricultural industry. With agriculture being a key component in food security and economic stability of the country, it is important to understand the variability of drought and its effects on the water balance and related crop yield, to provide key stakeholders with critical information for use in the planning, decision making and implementation of drought adaptation and mitigations strategies. The climate variability of the water balance components was investigated on a temporal scale for different seasons. It was discovered that soil moisture, transpiration and yield were only significantly affected during extremely dry El Nino years, where there was no prior moisture surplus at the start of the growing season. The sensitivity analysis of SWAP model's performance on yield, stomatal resistance and rooting depth, revealed that the observed and simulated yield values were poorly correlated, with an R^2 value of 0.0139, while increasing stomatal resistance and rooting depth led to an increase in the overall yield. The depletion of total available water (TAW) and readily available water (RAW) scheduling criteria showed great potential to be used in irrigation scheduling as they were able to detect and administer adequate irrigation depths and increase yield under drought conditions. A linear fit between the Evapotranspiration Drought Index (ETDI) and Soil Moisture Drought Index (SMDI) showed that the two were marginally correlated, yielding an R^2 value of 0.2117, where SMDI detected more extreme drought events, while ETDI detected a higher frequency of occurrence in Central Farm.

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Chapter 1 – Introduction

1.1 Motivation

With 70% of the world's poor living in rural areas and agriculture being their main source of employment, many of them find themselves in a precarious situation where their livelihoods are being jeopardized by land and water depletion and degradation, posing a threat to agricultural production, and endangering food and agriculture security in the world (World Bank, 2015). Belize, a developing country in the Caribbean' is abundant in water resources, has a suitable climate and sufficient arable land fit for agriculture with 38% of the its total land cover suitable for farming (FAO, 2011). Like much of the world's poor, the agricultural sector is the major foreign exchange earner for Belize as it contributes 15% of the country's GDP through the exportation of sugar, citrus and banana and employs approximately 19.5% of the population (FAO, 2015). In the United Nations World Water Development Report in 2009, however, it stated that the number of reported disasters have increased significantly between 1990 and 2006, particularly hydrometeorological disasters such as droughts, floods and tropical storms with floods and drought being the most frequent extreme events. Due to the geographical location of Belize, the country is not immune to such disasters.

Accurate knowledge of the effect of drought on water balance and crop yield is crucial for the sustainability of agriculture in Belize, as the frequency of drought is expected to increase with shifting rainfall patterns in the Caribbean and increase in temperatures due to climate change, making mitigation of these effects a priority (IPCC,2013). Although drought has been shown to occur frequently in Belize and the wider Caribbean, a lack of resilience to the disaster makes it difficult for the government, policy makers and farmers to plan, adapt and combat the adverse effects the water and agriculture industries face with an even further expected increase in drought frequency due to climate change (Farrell et al.,2010). This limitation in resilience is due in part to the country's heavy economic reliance on tourism, fisheries and agriculture for the maintenance of its GDP, all climate sensitive sectors, increasing its vulnerability to climate change, despite adaptation strategies being constrained due to high implementation costs on the local government (IPCC WGII AR5, 2014).

A lack of information sharing, expertise and utilization of meteorological data in the estimation of productivity has led to the heightened uncertainty of the effects of drought on Belize's agricultural industry (MOA, 2016). Accurate recording, dissemination, utilization and technical support of quality meteorological data pertinent to drought monitoring and crop growth estimation can offer possible early warning, improved decision making and possible solutions to the challenge of food and water security in Belize by increasing yields. While data access is just one issue, there are a limited number of fully functional agrometeorological stations in key areas of crop production in Belize, making it difficult to accurately monitor the variability of the effect of drought on crop growth (NMS, 2016).

Sugar cane, citrus and banana continue to be the major crops produced in Belize mainly for exportation, together with vegetables grown mostly for domestic consumption by small farmers (CCCCC, 2016). Due to recent commitments made to reduce poverty and hunger, investments are being made to improve the production of subsistence farmers, who mainly produce vegetables (FAO, 2016). This sector faces significant challenges as it is prone to pest and diseases, high production costs and most vulnerable to the impacts of climate change as the farmers do not have sufficient financial resources to cope and recover from drought (MOA, 2016). The country is at risk of substantial financial losses to its main income generator as was seen when the sugar and corn industry in the north suffered devastating impacts as a result of drought, which led to approximately US$14.2 million and 28,309 acres of crops in damages in 2015 affecting 4,383 farmers (DFC, 2016).

The potato (Solanum tuberosum) crop was chosen to be the focus of this study as it is the world's fifth most important food crop and one of the most important staple crop in the world's poorest regions and can provide 15% or more of the daily per capita calorie intake (RTB, 2016). Being rich in key nutrients such as pro-vitamin A, potato can significantly improve nutrition and food security in Belize and aid in meeting targeted goals to reduce poverty and hunger (CGIAR, 2016).

Studying soil water balance and implementing simple irrigation techniques such as drip irrigation and sprinkle irrigation can improve crop water use efficiency and limit the restraints of seasonal production of some vegetables (Rowell, 1994). With the availability of computer models that focus on the crop water balance, such as the Soil, Water, Atmosphere and Plant Model (SWAP), we can predict the length of the growing season, yield, and water use allowing us to choose suitable crops to grow, given the present climatic conditions and discern irrigation timing and amount (Alterra, 2008; Rowell, 1994).

1.2 Research Questions

1. What is the intra- and inter-annual variability in the water balance and related yield of the potato crop grown in Belize, as derived from the SWAP model?
2. What is the sensitivity of the SWAP model outputs to key crop parameters?
3. Can SWAP be used to improve irrigation planning in Belize?
4. What is the relationship between agricultural drought indices in Belize?
5. What is the occurrence and severity of drought events and how do these affect crop yield?

1.3 Organization

The Organization of the dissertation is outlined below:

Chapter 1

The introductory chapter outlining the motivation and aims of the study and providing research questions that will be addressed throughout the dissertation.

Chapter 2

A description of Belize and the study area Central farm is given in this chapter along with background and literature review of precipitation variability, drought and the water balance.

Chapter 3

A description of the methodology and materials is given in this chapter with soil, crop, meteorological driving data, SWAP and key aspects (initial/boundary conditions, derived data (such as water retention parameters and irrigation switches) and drought indices calculations.

Chapter 4

This chapter is divided into three main areas discussing (1) the climate variability of the water balance components of the potato crop, calibration of the model and yield (2) A case study done in Central Farm with different irrigation scheduling criteria and sensitivity analysis of stomatal resistance and rooting depth (3) Drought Indices: calculation and statistical analyses in the determination of drought.

Chapter 5

A summary of the main results obtained for each research question along with limitations and recommendations for future work.

Chapter 2 – Background and Literature Review

2.1 Description of Study Area

Belize is located on the Caribbean coast of Central America bordered to the North by Mexico and to the West and South by Guatemala (Figure 1), lying between 15°45’ to 18°30’ N and 87°30’ to 89°15’W (NMS 2016). The topography is low and flat along coastal and northern regions while low mountains reaches 3685ft in the central and southern regions. Belize experiences a wet and a dry season from June to November and December to May, respectively. According to the Köppen-Geiger climate classification, the North is classified as a Tropical Savanna (Aw) climate, Central, Coast and West as a Tropical Monsoon (Am) climate while the South experiences a Tropical Rainforest (Af) climate.

Figure 1. Location of Belize (left) in Central America and the Caribbean between 15-18°N and 87-89 °W showing surrounded countries and the Caribbean Sea with the Cayo district outlined in red and Central Farm identified by the blue dot (left) and the relative area of Central Farm (right) (Google Earth, 2016).

The mean annual rainfall across Belize ranges from 1524mm in the north to 4064mm in the south with mean temperatures varying from 27°C along the coast to 21°C in the mountainous areas (NMS,2016). Although detailed soil properties are limited, the general soil textures and types are shown in Figure 2:

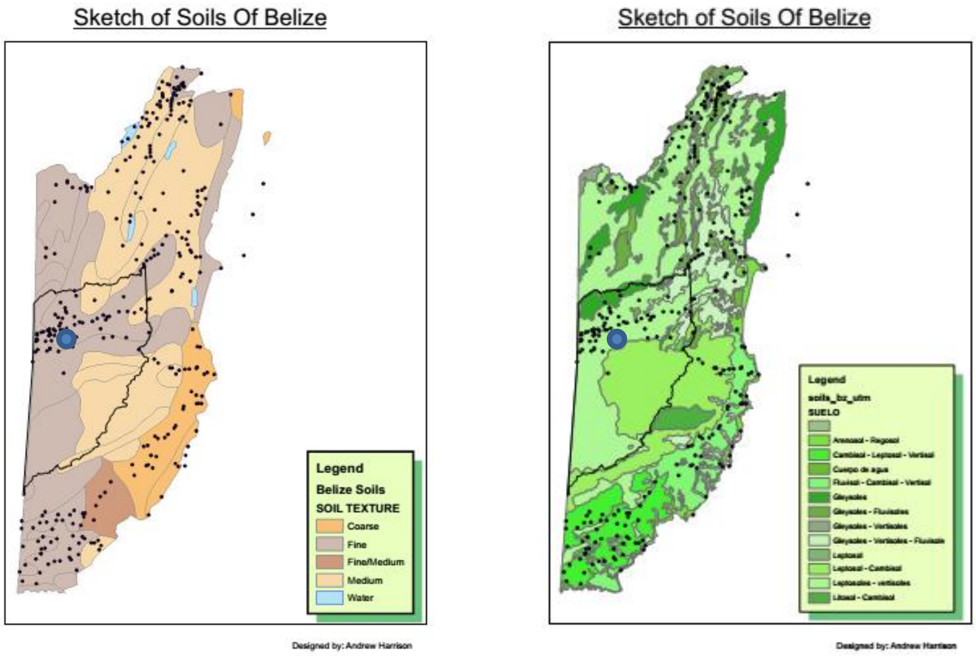

Figure 2. Maps of soil textures and types of Belize with Central Farm indicated by the blue dot and black dots representing the location of agricultural farms (Ministry of Agriculture, 2016).

2.1.1 Central Farm

The study was conducted on Central Farm in the Cayo district of Belize located inland at latitude 17°11'N and 89°W. At an elevation of 90m, Central Farm is tropical, hilly region with an average temperature of 26.3°C and total rainfall of 1797.6 mm annually averaged over the period 1971-2016 (NMS, CRCC,2016). During the warmer months, May, June and July (MJJ), the average temperature is 28°C, while in the colder months, December, January, February (DJF), the average temperature is 23.9°C (CRCC, 2016).

The Central Farm growing area consists of fine textured, fluvisol, cambisol and vertisol soil types suitable for growing a variety of crops. These soils have a large surface area due to their small particle size and pore space making them more hygroscopic. They have a higher soil water retention and are able to hold more water per volume compared to sandy soils (Rowell, 1994). Soils in this area are poorly drained with high water tables; both undesirable conditions as they result in water-logging in extreme rainfall events (CCCCC, 2016). In extremely dry conditions, potato growers use drip irrigation to provide supplemental water from wells in the area in times of limited rainfall with daily or three-day interval application as the need arises (MOA, 2016).

2.1.1.1 La Rouge Potato (Solanum Tuberosum L.) Crop

Tubers such as potato can be used to improve food security, nutrition and income in countries such as Belize since it is a major cash crop, rich in key nutrients and provide 15% more daily per capita calorie intake than cereals (RTB, 2016). On average, 150 acres of potato are planted in Central Farm of the total 210 acreages (MOA, 2016). It has been gaining popularity among policy makers and land use planners as a potential substitute to cereals because of its higher water use efficiency (Liu et al., 2006). Despite being efficient water users, the La Rouge potato is a drought sensitive crop (Yuan et al., 2003). In the Central Farm area, 95 % of the potato crop is irrigated to account for the erratic precipitation in the area (MOA, 2016). The La Rouge potato vulnerability to drought has been attributed mainly to its shallow rooting system and its limited ability to recover after a period of water stress (Iwama et al., 2006). A summary of the optimum environmental conditions for the growth of this species of potato in Central Farm can be seen in Table 1.

Table 1. Optimum conditions for the cultivation of the La Rouge potato crop in Central Farm, Belize (CGIAR, 2013).

Crop	Potato (Solanum Tuberosum L.)
Growing season length (days)	90
Killing Temperature (^{o}C)	-1
Min. Optimum Temperature (^{o}C)	15
Max. Optimum Temperature (^{o}C)	25
Min. Optimum annual Precipitation (mm)	500
Max. Optimum annual Precipitation(mm)	800
Start of Growing season	Mid Nov/Mid Dec

2.2 Drought

Drought is a stealthy natural hazard with different impacts from region to region not easily definable or understood (NDMC, 2016). Generally, drought can be defined as a deficiency of a region's water supply often triggered by extending periods of below average precipitation (NDMC, 2016). Drought can cause significant losses in a number of areas namely agriculture, water resources, economic and other environmental sectors (Trotman et. al, 2008). In agriculture, drought can affect crop quality and limit yield and the geographical regions where crop production is possible (Thakur et al., 2010). The agricultural sector is highly at risk to drought since it utilizes 70% of the world's fresh water resource (World Water Assessment Program, 2012). Seven of the top 36 water-stressed countries can be found in the Caribbean with the highest water stress scores showing the regions vulnerability and the need for resilience to drought (WRI, 2013).

2.2.1 Types of Drought

Drought has been classified climatologically and hydrologically by Wilhite. et al., (1985) into four main types as follows:

1. Meteorological drought: a result of prolonged absence of precipitation, high temperatures, low humidity which increases evapotranspiration for a specific region.
2. Agricultural drought: drought affecting agricultural production and occurring when there is precipitation shortages and soil moisture deficit and water requirements of plant are not met.
3. Hydrological drought: a slow process drought occurring when meteorological conditions causes reduction in the water levels from reservoirs, streams, lakes, rivers, aquifers etc.
4. Socio-economic drought: the correlation of the supply and demand of water resources for household water supply and hydroelectric power with the above-three mentioned drought types resulting in huge socio-economic impacts.

2.2.2 Drought Indices

Several drought indices have been developed to depict, monitor and quantify the onset, severity and duration of drought. In the Caribbean, through the initiatives of the Caribbean Institute for Meteorology and Hydrology (CIMH) and CARICOM member states, A Drought Early Warning and Risk Reduction system has been developed and operational since 2009 known as the Caribbean Drought and Precipitation Monitoring Network (CDPMN) under the Caribbean Water Initiative (CARIWIN) project (Trotman et al., 2008). Currently, the only structured drought monitoring system in the region, CDPMN incorporates the Standardized Precipitation Index (McKee et al., 1993) and Deciles (Gibbs and Maher, 1967). Both meteorological drought indices are used as a support for hydrological and agricultural drought forecasting, disseminating advisory information to regional governments (Farrell et al., 2010).

While CDPMN provides useful information on meteorological drought adaptive to hydrological and agricultural drought, it is fairly generic as it lacks full representation of the other two types of weather related drought and can be enhanced by the integration of agricultural drought indices, which would provide sector specific information making it easily applicable to the agriculture sector. Due to the sensitivity of agricultural crops to soil moisture in different aspects of crop development, agricultural drought indices must take into account vegetation type, crop growth and root development, soil properties, antecedent soil moisture condition, evapotranspiration, and temperature, components that are not fully assimilated in meteorological drought indices (Narasimhan & Srinivasan 2005). In this study the Evapotranspiration Deficit Index (EDTI) and the Soil Moisture Deficit Index (SMDI) will be investigated in the Central Farm area of Belize and are defined as follows (see Section 3.3.3 for in depth calculation of these indices):

I. **Evapotranspiration Deficit Index (EDTI)**: is calculated using weekly water stress ratio (WS), a function of actual evapotranspiration and reference evapotranspiration using model output, where WS values range from 1 to 0, with 1 indicating no evapotranspiration and 0 indicating evapotranspiration occurring at the same rate as reference crop evapotranspiration(ET) (Narasimhan & Srinivasan 2005).

II. **Soil Moisture Deficit Index (SMDI)**: is calculated using daily model output of available soil water in the root zone averaged over a 7-day period to get weekly percentage soil water deficit (SD), where SD values range from -100 to +100 indicating very dry to very wet conditions. SD values for all the sub-basins are scaled between -100 and +100 and are spatially comparable across different climatic zones (humid or arid) (Narasimhan & Srinivasan 2005).

2.2.3 The effect of drought on the potato crop

Drought conditions causes a decrease in soil moisture content available for crop use in photosynthesis and growth, limiting total biomass production in plants and can shorten growing periods (Ashraf, 2004, Kumar et al., 2007). The most sensitive development stages susceptible to water stress as a result of drought are the seed germination and early seedling growth in the emergence development stage (Heshmat et al., 2011). In addition to this, water stress during the tuber initiation period can lead to fewer and smaller tubers susceptible to common scab disease, dumbbell-shaped, knobby, or pointed-end tubers and hindrance of the overall yield production (Annandale et al., 2005; MacKerron and Jefferies, 1988). Water stress experienced during tuber bulking, the longest growth development stage, however, has the most detrimental effects on the potato growing season and final yield (Annandale et al., 2005).

2.3 Components of the soil water balance

The soil water balance can generally be described by Equation [1] and presented schematically as in Figure 3:

$$\Delta \boldsymbol{PAW} = \boldsymbol{P} + \boldsymbol{I} - \boldsymbol{R} - \boldsymbol{D} - \boldsymbol{E} - \boldsymbol{T} \qquad [1]$$

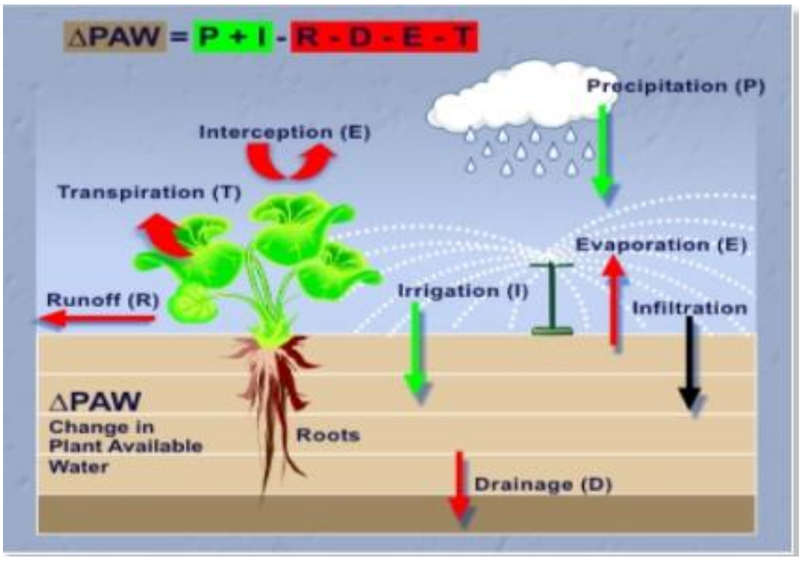

Figure 3. Schematic of the soil water balance components (Annandale et al., 2005)

where ΔPAW is the change in Plant Available Water or Storage Change, P is the Rain (Precipitation), I is the Irrigation, R is the Runoff, D is the Drainage, E is the Evaporation from soil surface and Interception and T is the Transpiration by the plant. Drought tolerance varies both spatially and temporally and is based on environmental conditions such as light intensity, soil type and atmospheric demand which influences the water balance (Tardieu, 2012). The following subsections will discuss each of these water balance components and their involvement in improving drought tolerance and water use efficiency.

2.3.1 Precipitation

Precipitation is the primary input of soil water in the vadose zone (Rowell, 1994). In the study area, the El Nino Southern Oscillation (ENSO), the coupled atmospheric-oceanic process involving the anomalous warming (El Nino) or cooling (La Nina) of the sea surface temperatures (SSTs) and shifting patterns of sea level pressure (SLP) across the tropical Pacific, affects the inter-annual precipitation variability (Giannini et al., 2001). The anomalous warming of the SSTs in the tropical Pacific and anomalously high SLP in the tropical Atlantic (El Nino) results in subsidence and divergent surface flow over the Caribbean leading to a reduction in precipitation over the area (Chen and Taylor, 2002). Conversely, weaker SLP and warmer SSTs in the tropical Atlantic (La Nina) lead to enhanced precipitation (Giannini et al., 2001). The reduction of precipitation during El Nino years and in particular the growing season, causes the soil deficit to build up quickly especially in hot dry conditions (CIMH and FAO, 2016).

2.3.2 Irrigation

Irrigation, the secondary input of water into the soil profile, is used to replace the maximum soil water deficit (MSWD), which is the amount of water stored in the soil that is readily available for plant use (MAFF, 2015). Irrigation can also be used to increase water use efficiency by ensuring that an adequate amount of soil moisture remains in the soil during key crop growth stages. The irrigation depth is determined by water availability and species, soil water retention and climatic conditions that determine the atmospheric evaporative demand (Silva et al., 2010).

The soil water balance is used to plan irrigation timing and application depth to avoid water stress in plants (FAO, 1998). Irrigation should be applied before the onset of water stress, to restore the soil moisture content back to field capacity (θ_{FC}), which is the upper limit to the amount of water the soil profile can hold. This is done at the refill point (θ_t), the point at which water must be added to the soil to avoid the plant becoming water-stressed, after the depletion of the MSWD denoted as readily available water (RAW) in Figure 4 is achieved (FAO, 1998).

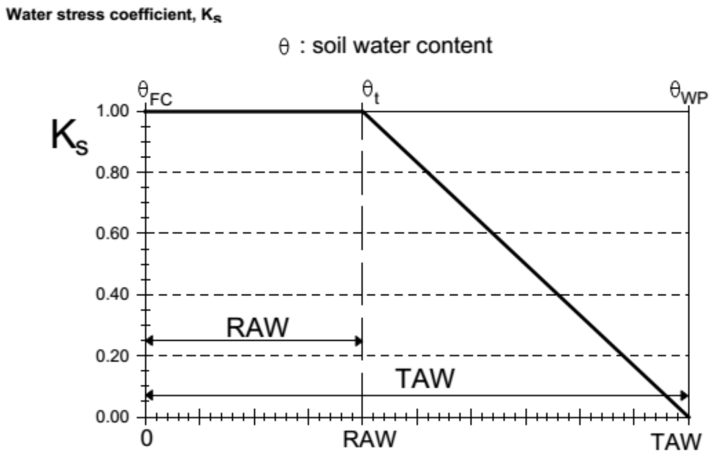

Figure 4. Soil water content in the root zone (FAO, 1998)

Below this limit, water stress can occur in the crop if the soil moisture is not replenished, depleting the total available water (TAW) in the soil and reaching the permanent wilting point (θ_{WP}), the lower limit to the amount of water held by the soil and up-taken by the plant, where the crop can no longer extract water (FAO, 1998).

2.3.2.1 Irrigation Types

Water use efficiency in potato has been increased substantially through the implementation of different irrigation methods such as drip irrigation (best method), sprinkle irrigation and surface irrigation (Saeed et al., 2008). Sprinkler, drip as well as the “bucket-method” irrigation methods have been used in the Cayo district and Central Farm area of Belize with hand dug wells fifteen to thirty feet depth as the main water source (Paget-Wilkes, 1986). In Table 2, different irrigation types, description, crop and benefits are summarized.

Table 2. Summary of Irrigation Methods and Properties (FAO, 1985)

Type	Description	Crop	Advantanges and Disadvantages
Surface (basin, furrow, border)	water under gravity flow to the surface flooded fields or small channels	maize, potato, vegetables sugarcane, citrus etc.	**adv**-small-scale schemes , easy construction & maintenance **disadv**-labour intenive, undefinable soils
Sprinkler	entire soil profile wetted, uniformity average application rate	vegetables & fruit trees	**adv**- simplest irrigation system, movable **disadv**- large labour force required to move pipes, uniformity affected by wind
Drip	water under presssure through a pipe system (emmitters),only root zone wetted, frequent slow application(1-3 days)	vegetables, sugarcane & soft fruit	**adv**-eficient water use, ideal for scarse water & labour **disadv**- requires technical expertise, high maintenance, costly installation

2.3.3 Evapotranspiration (Evaporation and Transpiration)

Evapotranspiration is partitioned as the loss of water by soil and canopy evaporation transpiration (Lawrence et al., 2007). Potential soil evaporation is influenced by temperature, solar radiation, humidity of the air and wind-speed (Rowell, 1994). In dry soil conditions, the soil suction increases, decreasing the pore spaces within the soil resulting in a small gradient between the dry atmosphere and soil air causing a reduction in the soil evaporative rate (Wang et al., 2016). A decrease in the soil hydraulic conductivity in drier conditions also results in inadequate water inflow to the surface to account for the water loss by evaporation and may lead to a lower actual evaporation rate (Jermar, 1987).

Evaporation also occurs through the stomatal openings of the leaves when vegetation is present in a process called transpiration (Rowell, 1994). Transpiration is restricted by a small stomatal resistance during the day when the stomata are open to allow for gaseous exchange between water vapour and carbon dioxide (CO_2) necessary for photosynthesis (Farquhar, 1982). When soils are dry, the plants undertake adaptive measures to conserve water and minimize loss, by closing their stomata and shedding leaves, limiting transpiration as a result of a reduction in available soil water (Rowell, 1994). In the interim, photosynthesis and final crop yield is affected as stomatal closing also cuts the supply of the influx of CO_2 (Collatz et al., 1991).

In the presence of vegetation and a high evaporative demand, potential transpiration rate is high to match the rate of loss of water to the atmosphere and with adequate soil moisture, actual transpiration rate is high and equal to the potential transpiration rate (Rowell, 1994). When soil moisture decreases because of limited rainfall or drought conditions, actual transpiration reduces below the potential transpiration because there is not enough water in the soil to supply to the plants quick enough to satisfy the atmospheric demand (Murataet al., 2013). The net effect of these processes is the reduction of soil moisture when precipitation is limited and temperatures, wind-speed and solar radiation are high.

2.3.3.1 Stomatal Resistance

When there is water stress in plants, the reduction in stomatal conductance is one way in which the plant tries to conserve water and minimize water loss and may be a key component in creating drought tolerance in plants (Lawson, 2009). Stomata resistance in plants is predisposed to climate and water availability resulting in variable responses amongst crop varieties with resistance increasing when the crop undergoes water stress or water availability becomes limited (FAO, 1998). These cells, however, are capable of adapting to varying environmental conditions (Zeiger et al., 2002). It is this characteristic that enables the cells to play a key role in regulating the plants' water status and photosynthetic capabilities (Lawson, 2009).

In water stress conditions, plants control stomatal aperture through the release of abscisic acid (ABA) causing the stomata to close reducing transpiration and evapotranspiration (Okamoto et al., 2013). Apart from the reduction in transpiration due to stomatal closing, net photosynthesis is also affected as intercellular carbon is depleted (Collatz et al., 1991).

2.3.4 Infiltration and Runoff

Surface runoff occurs when the infiltration capacity of the soil, the ability of water to flow from the soil surface into the soil is exceeded by rainfall intensity and water cannot penetrate into the soil fast enough resulting in runoff (FAO, 1993). The infiltration rate, the rate at which water is able to flow into the soil as defined by Morin and Benyamini (1977) is given by Equation [2]:

$$I_t=(I_i-I_f).\boldsymbol{e}^{-\gamma \boldsymbol{p}\boldsymbol{t}_t}+\boldsymbol{I}_f \qquad [2]$$

where I_i is the initial infiltration rate of the soil (mm h^{-1}), I_f is the final (constant) infiltration rate of the soil (mm h^{-1}), t is the time from the beginning of the rain (hours), γ is the soil coefficient and p is the rain intensity (mm h^{-1}).

Infiltration and surface runoff are affected by the intensity and duration of the rain (Rowell,1994). If gentle rains occur, infiltration will occur providing the soil is not saturated resulting in no accumulation of runoff and contribution of moisture to the soil profile (Rowell, 1994). In excess precipitation, where infiltration capacity is exceeded, there is a small soil suction and surface ponding occurs and in some cases, leads to surface runoff (Kroes and van Dam, 2003).

2.3.5 Bottom Flux (Drainage)

Free drainage in the soil profile and bottom flux is determined from the hydraulic gradients between the bottom of the soil column and water table beneath (Campoy et al., 2013). These fluxes are dependent of the hydraulic conductivity of the lowest soil layer (Kroes and van Dam, 2003). Bottom flux values within the soil profile can be altered by either drying (evaporation) or wetting (rainfall or irrigation) events where negative bottom flux values would indicate that the moisture remained in the soil whereas with positive bottom flux values, the soil moisture was being lost through evaporation or by transpiration in the presence of crops (Zeng, Y., 2012).

2.3.6 Storage Change

Soil moisture storage in an important factor in the detection of drought as its spatial and temporal variability are closely related to the phenomenon (Ahmad et al., 2010). It is defined as the amount of water that can be stored in the soil at a particular time based on the soil properties such as soil texture and type and the amount or organic matter contained in the soil, with a maximum soil storage at field capacity (Ritter, 2012). As soil moisture storage change (STOR) is a key element in the water balance and agriculture, and defined by Equation [1], negative values indicate that the precipitation is not able to meet the demand of the evapotranspiration and water is extracted from the soil, positive soil storage change values indicates an excess of soil moisture and zero indicates that the soil is at field capacity (Moiwo et al., 2011).

2.4 Rooting depth

The depth of the root of crops is the most important factor in relation to drought due to its direct contact with soil and its role in root water extraction to provide water and nutrients to the plants necessary for crop production (Chauhan et al., 2015). The rooting depth governs the extent to which the root can explore the soil volume and extract soil moisture and facilitate the flow of water from the soil to the plant (Rowell, 1994). The soil water storage (SWS) capacity is defined as the total amount of water that is stored in the soil within the plant’s root zone determined by the rooting depth and soil texture

(MAFF, 2015). Increasing rooting depth increases the volume of water that is stored in the soil as more water is available for extraction by the plant roots to be used in photosynthesis (Rowell, 1994). Drought tolerant varieties of potato have deeper rooting systems and higher dry root weight, correlated to drought recovery and have high yield stability in drought prone regions (Steckel and Gray, 1979, Rossouw and Waghmarae, 1995, Deguchi, et al., 2010). As a result, transpiration rates increase with the increase in water flow by the extension of the rooting zone (Rowell, 1994).

2.5 Computer modelling and Agriculture

Agricultural computer models such as SWAP (Kroes et al., 2008), WOFOST (Boogaard et al., 2014), DSSAT (Hoogenboom et al., 2015) can be used predict the length of growing seasons and choose suitable crops depending on environmental conditions and reduce water stress conditions (above or below normal precipitation) by simulating transport processes and yield (Rowell, 1994). Simulation modelling using agricultural models to determine soil water balance and yield is not commonly done in Belize (MOA, 2016). Only a limited number of the application of the SWAP model in tropical regions can be found in current literature. However, it has been widely used in temperate and arid regions as SWAP was used by Giuseppina and Garofalo (2005) to simulate water and solute transport in a crackly clay soil, Mostafazadeh-fard et al. (2008) to predict yield and soil salinity for sustainable agriculture in Iran, Martínez-Ferri et al. (2013) to simulate soil water balance in an application for irrigation water management and climate change adaptation in citrus and Sarwar et al. (2000) to evaluate the performance of drainage systems in semi- arid zones in Pakistan.

In the Western Caribbean, Ruiz and Utset (2003) used SWAP to predict water use and crop yields for potato and sugarcane in Cuba. The results showed that there is potential for SWAP to be adapted in Belize, which has similar climate and soil characteristics as those of Cuba, and R^2 values of 0.85 and 0.69 for a 95% confidence level were obtained in the comparison of simulated and measured soil moisture content and potato yield, respectively (Ruiz and Utset, 2003). Although the 0.69 R^2 value could be considered low, the soil hydraulic properties used in the simulation were not taken from the location where the field observations were made, though the soil type was the same (Ruiz and Utset, 2003).

Chapter 3 – Methodology

In this study, the Soil Water Atmosphere and Plant (SWAP) model was used to simulate the growth of the La Rouge (Solanum tuberosum) potato crop, the water balance and to schedule irrigation in the Cayo and Belize districts using meteorological variables provided by the National Meteorological Services of Belize, and agriculture and soil data from the Ministry of Agriculture in Belize. SWAP model utilizes radiation(kJm^{-2}), minimum (^{o}C) and maximum (^{o}C) temperatures, humidity (kPa), wind speed (ms^{-1}) and rainfall (mm) as its meteorological drivers along with soil hydraulic parameters, manual input of planting seasons and irrigation schedules and amount to simulate crop growth and yield, water balance components and soil moisture contents. The limited availability of agrometeorological stations in key agricultural areas restricts this study in Belize to the locations explored in sections 2.1.1 and 2.1.2. As a result of this, the methodology delineated in this chapter takes into account the limited availability of data in addressing the research questions.

3.1 Description of the SWAP model

SWAP 3.2, developed by Alterra and Wageningen University, is designed to simulate the transport of water, solute and heat in the vadose zone of the soil at field scale level throughout crop growing seasons (Van Dam et al., 2008). These transport processes occur in the vertical resulting in SWAP being a one dimensional, vertical model with only a field scale focus in the horizontal as stated in (Kroes and Van Dam, 2008). Soil water flow is resolved in SWAP by employing the implicit, backwards, finite difference Richards equation which utilizes user-specified boundary conditions where SWAP uses potential evapotranspiration (ET_{p0}), irrigation and rainfall as upper boundary conditions and free drainage was specified as the bottom boundary condition (Haverkamp et al. (1977) and Belmans et al. (1983)).

In addition to this, potential evapotranspiration can be generated by SWAP using the Penman-Monteith equation and daily meteorological input variables or by providing reference evapotranspiration values and crop factor; the former is used in this study for uniform surfaces (wet and dry vegetation, bare soil). It is then used to calculate the potential soil evaporation rate (E_p) by taking into account reduction of solar radiation due to shade by crops or instances when the crop is wet by using the Goudriaan (1977) and Belmans (1983) method. Potential soil evaporation rate is equal to:

$$E_{\mathrm{p}}=E_{\mathrm{p0}}\boldsymbol{e}^{-\mathrm{K_{gr}}\boldsymbol{LAI}} \qquad [3]$$

where K_{gr} (-) is the extinction coefficient for solar radiation, LAI is the leaf area index, and E_{p0} is the potential evaporation rate. SWAP calculates the potential transpiration rate (T_p) by assuming that the total evapotranspiration rate where the canopy is dry corresponds to ET_{p0} and the fraction of the day that the crop is wet, W_{frac} (-) resulting in T_p being:

$$T_{\mathrm{p}}=(1.0-W_{\mathrm{frac}})ET_{p0}-E_{p} \qquad [4]$$

SWAP reduces E_p to actual soil evaporation (E_a) by either (1) taking the minimum of potential evaporation rate, (2) the maximum evaporation rate (E_{max}) in the top soil according to Darcy assuming a minimum allowed pressure head in the atmosphere (Black, 1969), or (3) an empirical evaporation function (Black et al. 1969; Boesten & Stroosnijder 1986).

Similarly, potential transpiration rate is reduced in SWAP by assuming that water and salinity stress are multiplicative and actual root water extraction is calculated from:

$$S_a(z) = \alpha_{rw}\,\alpha_{rs}\,S_p\,(z) \qquad [5]$$

where α_{rw} (-) and α_{rs} (-) are the reduction factors due to water and salinity stresses, respectively and by integrating S_a (z) over the root layer yields the actual transpiration rate T_a (cm d^{-1}).

Additionally, the detailed simulation of crop growth by SWAP incorporates the World Food Studies (WOFOST) crop model which simulates photosynthesis and crop growth accounting for water and salt stress with light inception and carbon dioxide (CO_2) assimilation as growth driving factors. Relative transpiration provides a measure of water stress on photosynthesis in the model (Kroes and van Dam, 2008). In SWAP, the WOFOST simulation process begins at emergence and continues throughout the phenological development stages from 0 to 2 dependent on development rate which is controlled by day length and or temperature. Development rates are determined by the temperature sum, where in tropical regions an effective temperature T_{eff} (^oC) is calculated as function of daily average temperature T_{air} (^oC) and $T_{eff} = 0$ at T_{air} of 9 to 14 (^oC) (Angus et al., 1981). Crop growth is classified by daily assimilation rate, which is treated as a function of intercepted light, initial light use efficiency and maximum leaf CO_2 assimilation at light saturation, taking into account reductions due to water or salinity stress and low temperatures (Kroes and Van Dam, 2008). The net assimilation available for structural matter of the crop into storage organs is the gross assimilation minus the respiration rate of the crop which is converted into dry matter (Kroes and Van Dam, 2008).

Furthermore, SWAP can be used for irrigation planning to minimize water stress, restore the water balance and in turn, maximize yields throughout the growing season. The water balance simulations can be used to optimize irrigation schedules. The model employs two irrigation methods, fixed, where time and depth are defined or scheduled irrigation with specified criterion to ascertain when and how much irrigation should occur based on crop development stage (Kroes and Van Dam, 2008). In the scheduled method, six timing criteria for irrigation scheduling prescribed in SWAP are allowable daily stress, allowable depletion of readily available water in the root zone, allowable depletion of totally available water in the root zone, allowable depletion amount of water in the root zone, critical pressure head or moisture content at sensor depth and fixed weekly irrigation (root zone to field capacity) and only occurs when the crop is present (Kroes and Van Dam, 2008). On the other hand, two application criteria are utilized by the model namely the back to field capacity (+/- specified amount) and fixed irrigation depth, where irrigation is applied to either bring the soil moisture content to field capacity or by adding irrigation depth specified by the user (Kroes and Van Dam, 2008).

3.2 Data Collection and Processing

3.2.1 SWAP Model Parameters

The SWAP model parameters utilized in the study are described in Table 3.

Table 3. List of soil types, crop type, SWAP model input factors and variables.

Soil Type		Fluvisol, cambisol and vertisol soils								
Crop Type	**Code Name**	potato								
	Full Name	La Rouge (Solanum Tuberosum) Potato								
Model Variables	**Code Name**	Runoff	Tpot	Tact	Epot	Eact	QBottom	Gwl	ETpot	ETact
	Full Name	Runoff	Potential Transpiration	Actual Transpiration	Potential Evaporation	Actual Evaporation	Bottom flux	Groundwater level	Potential Evapotranspiration	Actual Evapotranspiration
Input Factors	**Code Name**	θ_{sat}		α	n	l	K_{sat}		θ_{res}	
	Full Name	Saturated water content		α	n	l	Saturated hydraulic cond.		Residual water content	

3.2.2 Meteorological Data

Daily sunshine hours, minimum and maximum temperatures, wind speed and rainfall data were obtained from the agrometeorological station at the Central Farm representing the meteorological conditions experienced in Spanish lookout in the Cayo District where much of the potato crop is grown. The length of the dataset is 31 years from 1985 to 2015. As was expressed in section 1.1 and 3 missing and available data is a major issue and 35.8% of the observed sunshine hours were missing and the relative humidity in the area was unreliable, however, only 0.7%, 2.8%, 1.8% and 2.9% of rainfall, maximum temperature, minimum temperature and wind speed, respectively were missing.

To account for the missing values of minimum and maximum temperatures, wind speed and rainfall data, the long term 30 year climatological daily averages were calculated and used. In tropical humid regions, an estimate of actual vapour pressure, e_a, can be obtained by assuming that dew point temperature (T_{dew}) is near the daily minimum temperature (T_{min}) and Equation [6] was used to calculate the actual vapour pressure (kPa) used as the humidity parameter in the model (FAO, 1998).

$$e_a = e_0(T_{min}) = 0.611 \exp\left[\frac{17.27T_{min}}{T_{min} + 237.3}\right] \qquad [6]$$

Solar radiation data can be derived from air temperature differences by making use of the Hargreaves radiation formula seen in Equation [7]:

$$\mathrm{R_s} = \mathrm{k_{Rs}}\sqrt{(\mathrm{T_{max}} - \mathrm{T_{min}})\mathrm{R_a}} \qquad [7]$$

where R_a is the extra-terrestrial radiation [MJ m^{-2} d^{-1}], T_{max} is the maximum air temperature (°C), T_{min} is the minimum air temperature (°C) and k_{Rs} is the adjustment coefficient (0.16 to 0.19)(°$C^{-0.5}$). A k_{Rs} value of 0.16 was used for the interior location of Central Farm, where land mass dominates and air masses are not strongly influenced by a large water body in the replacement of the missing solar radiation values (FAO, 1998). The R_a daily values were determined using Equation [8] at the central farm station as follows:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \qquad [8]$$

where R_a is the extra-terrestrial radiation (MJ m^{-2} day^{-1}), G_{sc} is the solar constant with a value or 0.0820 $MJm^{-2}min^{-1}$, d_r is the inverse relative Earth-sun distance(Appendix1), $\omega_s$is the sunset hour angle (rad) (Appendix 1), φ is the latitude (rad) (Appendix 1) and δ the solar decimation (rad) (Appendix 1).

3.2.3 Agricultural Data

In order to compare crop yield simulated by the model, yearly yield data of Irish potato converted to kg/ha was collected and from the Ministry of Agriculture in Belize for the period of 2000 to 2014. The relevant soil type and texture, growing seasons and optimal conditions were also collected from the Ministry of Agriculture and the Consultative Group for International Agricultural Research (CGIAR).

3.2.4 Other Data

Since simulation modelling is not a frequent practice in Belize, the soil hydraulic parameters used in the model were taken from Wosten et al., (1999) using Mualem-van Genuchten parameters for the mostly fine to medium top and subsoil layer in the research area.

3.3 Model runs

3.3.1 No Irrigation

To investigate the climate-dependent variability of the water balance and yield of potato, a SWAP run was conducted using the detailed model potato crop file for a simulation period from 01/01/1985 to 31/12/2015 producing daily outputs of the modelled variables. Yearly water balance was set to be generated at the end of each simulation year. While the switches for the output of moisture, solute, temperature, and water balance were turned on, those of the soil temperature, water fluxes, artificial drainage and surface water reservoir were turned off. All switches for the water qualities of the chemical transport models such as PEARL for pesticides and ANIMO for nutrients were turned off and treated as controlled variables in this research. This simulation was conducted using inputted daily meteorological data at the station with reference evapotranspiration calculated by the model using the Penman Monteith method.

The crop growing season was standardized and kept as a controlled variable in this study by setting the crop emergence and crop harvest dates in the model to November 15 and February 15 respectively for each simulated year with no irrigation prescribed. The initial soil moisture content was derived from the initial ground water level which was chosen as -75 cm in equilibrium with the pressure head. Potential soil evaporation was calculated from the evaporation derived in SWAP based on the meteorological input data since no reference evapotranspiration was available and a soil evaporation coefficient of 0.35 from Black et al. (1969) was used to simulate the reduction of potential soil evaporation by using the reduction of maximum Darcy flux and maximum Black method along with 0.5 cm minimum rainfall value to reset Black method.

Due to limited availability of measured soil profile data in the Central Farm area and Belize as a whole, at maximum profile depth of 300 cm was chosen to represent the soil profile with two main soil layers based on data gathered from the Ministry of Agriculture in Belize and soil hydraulic parameters adapted from Mualem-van Genuchten summarized in Table 4 below:

Table 4. Soil hydraulic parameters at the top layer and sub layer of the soil profile (Wosten et al., 1999)

Layer	θ_{res} (cm^3/cm^3)	θ_{sat} (cm^3/cm^3)	α (cm^{-1})	n	K_{sat} (cm/day)	l
1	0.010	0.520	0.037	1.101	24.800	-1.977
2	0.010	0.480	0.020	1.086	8.500	-3.712

No hysteresis was taken into consideration for the soil water retention and a maximum rooting depth of 50 cm was chosen. The explicit method of the Richards equation was resolved numerically to simulate soil moisture in the vadose zone of the soil profile using unweighted arithmetic mean of the hydraulic conductivity and no lateral drainage to surface water was simulated. The simulation was performed using air temperature from the meteo file as the top boundary condition and a bottom boundary condition of a free draining soil profile with no solute transport, solute decomposition and heat flow.

A sensitivity analysis was done by varying stomata resistance and rooting depth at 25 s/m, 50 s/m and 100 s/m and 25cm, 50cm, 75cm, respectively.

The sensitivity of the model's performance in the prediction of crop yield was tested using statistical analyses such as a linear regression, correlation coefficient, maximum error (ME), root mean squared error (RMSE), coefficient of determination (CD), modelling efficiency (EF) and coefficient of residual mass (CRM) using equations 20 to 24 in Appendix 1, where ME gives the worst case performance of the Model, RSME tells how much the modelled values over-or under-estimated the observed values, CD is the ratio between the scatter of the modelled and observed values, EF is the comparison of the modelled to the averaged observed and a -EF means the average observed gives a better estimate than the simulated values and CRM is the tendency of the model to over-or under-estimate values (Martínez-Ferri et al., 2013). Identical values of simulated and observed would yield an ME, RMSE, and CRM of zero and CD and EF of 1 (Martínez-Ferri et al., 2013).

3.3.2 Irrigation

To investigate the effect of irrigation on crop growth, a case study was done using SWAP on the potato crop, with the settings described in section 3.3.1, by looking at how different irrigation schemes affected the transpiration and yield of the crop throughout the growing season. The Sprinkle-fixed irrigation method was tested by applying weekly irrigation depths of 1.5 cm in weeks 4-6 (after emergence), 4 cm in weeks 7-10 (tuber initiation) and 2cm in weeks 11-12 (maturity) while no irrigation was applied in weeks 1-3 and 13. The six scheduling irrigation timing criteria listed in section 3.1 were applied using the back to field capacity application criteria in all cases.

3.3.3 Calculation of Drought Indices

To determine severity of agricultural drought in Central Farm and compare the performance of the detection of drought, two agricultural drought indices were calculated using output from the SWAP model run for potato.

3.3.3.1 ETDI (Narasimhan & Srinivasan 2005)

The calculation of ETDI constitutes several components. Firstly, daily actual and potential evapotranspiration was converted to weekly water stress ratio (WS) yielding 52 weeks for each year. In Equation [9], the weekly water stress ratio is given as:

$$WS = \frac{PET - AET}{PET} \qquad [9]$$

where WS is the weekly water stress ratio, PET the weekly reference crop evapotranspiration and AET the weekly actual evapotranspiration (Narasimhan & Srinivasan 2005).

Long-term water stress (water stress anomaly) was also calculated for each week in a year by taking the median of the water stress of the week during the 31-year period (1985-2015), using Equation [10], given by:

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{MWS_j - \min WS_j} \times 100 \quad if\ WS_{i,j} \leq MWS_j$$

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{max\ WS_j - MWS_j} \times 100 \quad if\ WS_{i,j} > MWS_j \qquad [10]$$

where WSA is the weekly water stress anomaly, MWSj, the long-term median water stress of week j, max WSj, the long-term maximum water stress of week j, min WSj the long-term minimum water stress of week j, and WS is the weekly water stress ratio for i, the year from 1985 to 2015 and j, weeks 1 to 52. From the calculated WSA value, initial ETDI and EDTI for all other months were calculated using Equation [11] and [12] respectively.

$$ETDI_1 = \frac{WSA_1}{50} \qquad [11]$$

And

$$ETDI_j = 0.5\ ETDI_{j-1} + \frac{WSA_j}{50} \qquad [12]$$

3.3.3.2 SMDI (Narasimhan & Srinivasan 2005)

The calculation of SMDI, soil water deficit was calculated by Equation [13]:

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{MSW_j - \min SW_j} \times 100 \quad if SW_{i,j} \leq MSW_j$$

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{maxSW_j - MSW_j} \times 100 \quad if SW_{i,j} > MSW_j \qquad [13]$$

where $SD_{i,j}$ is the soil water deficit (%) ranging between -100 (driest conditions) and +100 (wettest conditions); $SW_{i,j}$ is the mean weekly soil water available in the soil profile; MSW_j is the long-term median available soil water in the soil profile; $max\ SW_j$ is the long-term maximum available soil water in the soil profile; $\min SW_j$ is the long-term minimum available soil water in the soil profile; for i, the year from 1985 to 2015 and j, weeks 1 to 52.

From the calculated SD values, the initial SMDI value and SMDI values for all other months were calculated using Equation [14] and [15], respectively.

$$SMDI_1 = \frac{SD_1}{50} \qquad [14]$$

$$SMDI_j = 0.5\ SMDI_{j-1} + \frac{SD_j}{50} \qquad [15]$$

SMDI ranges between -4 (driest conditions) to +4 (wettest conditions) and can be calculated down to the maximum rooting depth of 50 cm.

Chapter 4 – Results and Discussion

The following chapter presents the results obtained by the methodology outlined in Chapter 3 and analyses the water balance and yield to aid in the drought assessment of the potato crop in the study area. This first section in this chapter investigates the effect of the climate variability on the water balance and crop growth by studying inter-annual seasonal cycles in the water balance, the intra-annual variability of key variables relating to drought and crop growth and the sensitivity of the SWAP model to parameters and model switches in simulating yield over the growing season of the potato crop.

The second section in this chapter presents a case study done for Central Farm, to investigate transpiration and crop growth. The results presented include the evolution of the water balance when running the model for different irrigation methods, different values of stomata resistance and rooting depth, with emphasis on transpiration and yield during the growing season.

Lastly, the third section of the chapter assesses the occurrence and severity of drought events using the drought indices EDTI and SMDI and how they affect crop yield.

4.1 Climate Variability in the Soil Water Balance and Yield

The water balance components precipitation (Prec), soil evaporation (Eact), transpiration (Tact), surface runoff (RO), deep drainage (bottom flux, BF) and Interception (Int)determines the soil water balance and soil water storage change. If the input exceeds the output, the excess is denoted by a positive value in storage change (STOR) component. On the other hand, if the output exceeds the input, there is a decrease in soil moisture and a resultant negative STOR. The balance between these processes is important as it determines the rate of growth and development of vegetation. The main output components of the soil water balance are Eact and Tact with Tact being the most important component as it gives an indication of leaf area, water flow through the plant and stomata aperture which serves as the pathway for the influx of CO_2necessary for photosynthesis (Rodriguez-Garcia et al., 2007).

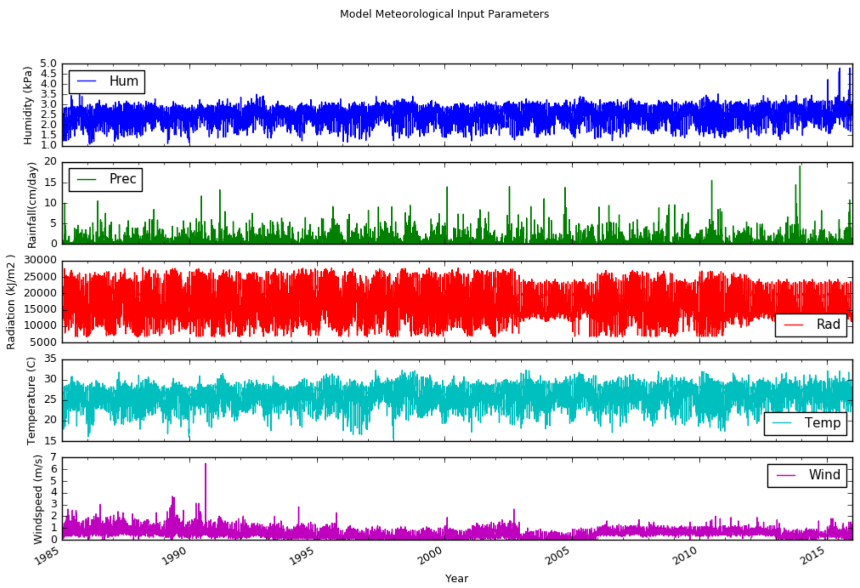

Figure 5. Time series of daily model meteorological input parameters for 1985 to 2015 showing Humidity (Hum), Rainfall (Prec), Radiation (Rad), Temperature (Temp) and Wind speed (Wind) at Central Farm, Belize.

The potential transpiration rate is dependent on the atmospheric demand which is influenced by the key meteorological input variables seen in Figure 5, such as temperature, wind-speed, radiation and humidity. However, despite the atmospheric demand, transpiration cannot occur without the availability of water in the soil, and it being able to move from the soil to the root to match the rate of loss of water to the atmosphere. The effect of these parameters on the water balance will be seen in the following sections.

4.1.1 Inter-Annual Seasonal Cycle

This section will discuss the changes in the soil water balance components on a seasonal timescale looking at the wet season (JJASON), the dry season (DJFMAM) and the crop growing season (DJF) derived by SWAP from daily meteorological and crop input parameters.

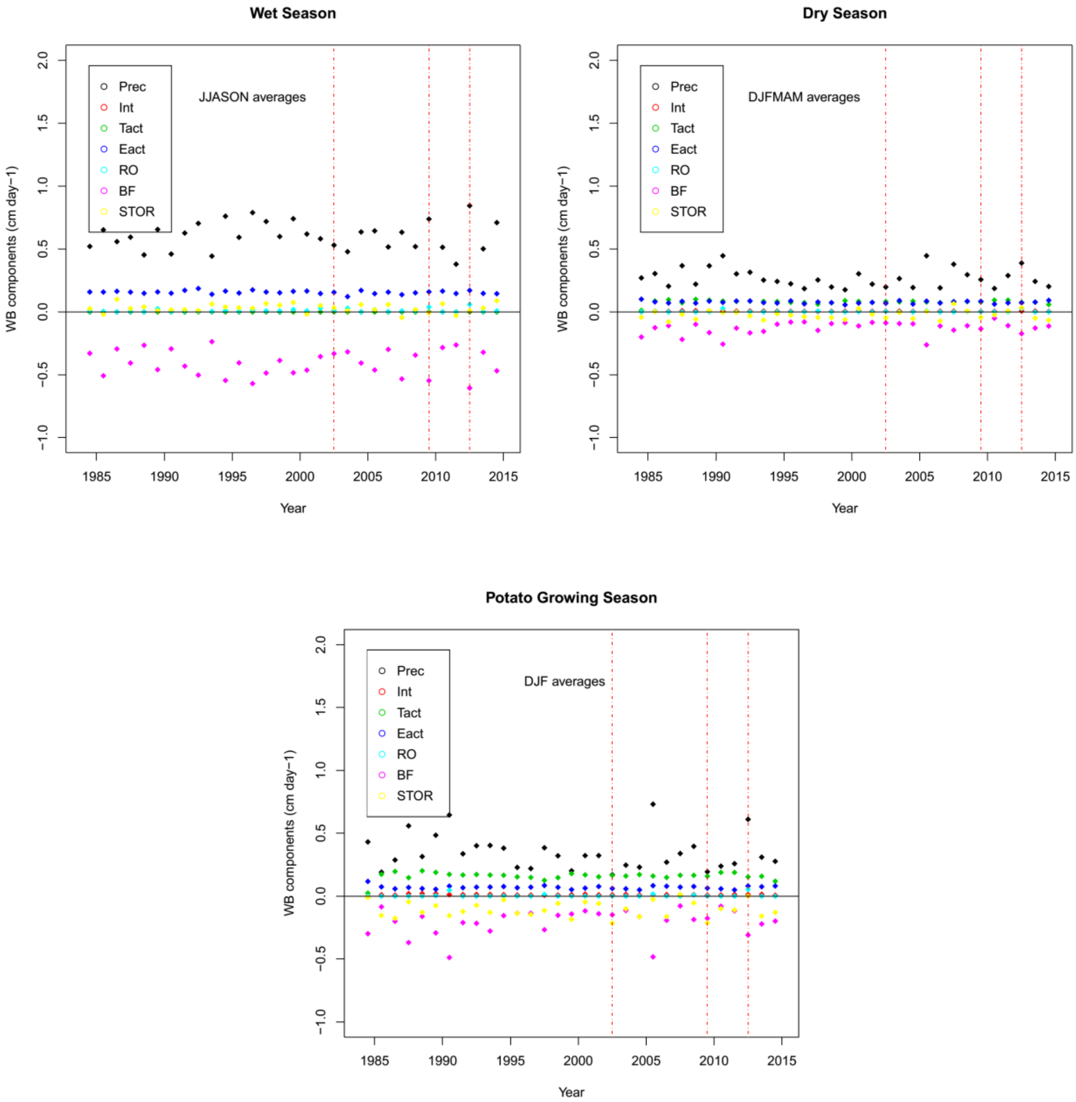

Figure 6. Water balance components (no irrigation) averaged over the wet season (top left), dry season (top right) and potato growing season (bottom centre) for Central Farm, Belize (simulated by SWAP, July, 2016).

In Figure 6, seasonal averages of seven soil water balance components, precipitation (Prec), interception (Int), actual transpiration (Tact), actual evaporation (Eact), runoff (RO), bottom flux (BF) and soil water storage (STOR) for the period (1985-2015) are displayed. Vertical lines highlights key years of interest, two dry El Niño years (2003 and 2010) and one wet year (2013). In the wet season, the soil water storage change is positive for most years and only slightly negative in 1986, 2001, 2008 and 2012 indicating that some water was extracted from the soil in these years. With more negative values of BF, highest values of precipitation, minimal to no RO and no Tact and Int, the soil moisture content was high. The evaporation was also the highest in this season due to more available water, higher temperatures, no crop growth and radiation to sustain soil evaporation. On the other hand, over the dry season, there are noticeable differences in the Prec, BF, STOR and Eact soil water balance components as precipitation input decreases and water loss increases with the inception of crop growth indicated by the presence of the Tact and Int components.

Soil water availability is critical in the DJF potato growing season with transpiration being the only useful water loss component as crop growth and production are impossible without it (Annandale et al., 2005). This is depicted in Figure 6 as transpiration values are highest during this season, second to precipitation, while water loss through soil evaporation has decreased as compared to the JJASON season. During this period, the largest reduction in STOR can be seen along with evidence of interception and less negative values of BF as the plants utilize the available moisture for growth.

A successful potato growing season requires adequate water supply to minimize water stress, however, drought conditions negatively affects the soil water balance and in turn, yield. Frère and Popov (1986) defined the humidity period or the growing season of a crop as the period when precipitation outweighs evapotranspiration loss by half, to ensure the crop has an adequate supply of water for growth. However, both DJF growing seasons for 2003 and 2010 were affected by moderate El Niño events with 0.9 and 1.3 above normal SSTs anomalies respectively, resulting in drier conditions (CPC, 2015). This is reflected in the soil water balance for these seasons where Tact values equalled that of the Prec values in 2003 and Prec was slightly higher than Tact in 2010, coupled with the loss from soil evaporation Eact in both cases. These conditions in 2003 and 2010 indicate that adequate moisture was not available and the possibility of water stress existed during both, which can significantly reduce crop yield. This was further justified in Figure 6 where two of the lowest STOR values were recorded and the BF were reduced for these years where the crops began to extract water from the soil storage. In 2013, the opposite was seen.

4.1.2 Intra-Annual Variability

This section will include the discussion of the intra-annual variability of key water balance components influenced by drought that affects the growth of potato.

4.1.2.1 Precipitation

For a successful potato production, adequate supply of water must be available in the vadose zone of the soil profile. With precipitation being the primary input source of water in the soil water balance, knowledge of its intra-and inter-annual variability is critical to the growing of potato. The intra-and inter-annual variability of this variable in the study area forms a bimodal trend with two peaks, one at the start of the wet season, between May to June and a second peak between September to October (Chen and

Taylor, 2002). The second node is used to supply the soil with adequate moisture necessary for emergence of the crop. In Figure 7, the two El Nino years (2003 and 2010) received below average rainfall during the growing DJF growing period whereas above normal rainfall was received for much of 2013.

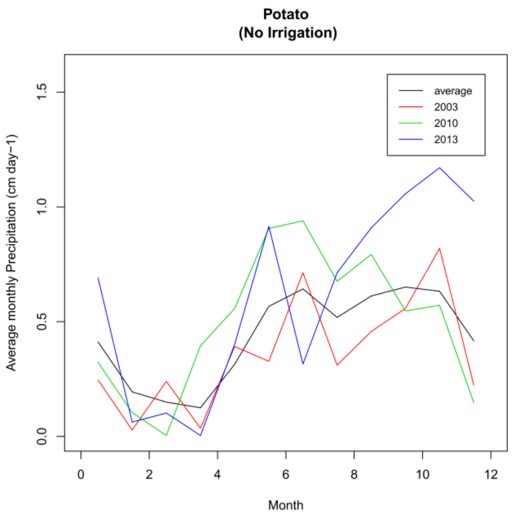

Figure 7. Monthly averages of precipitation for two dry El Niño years (2003, 2010) and a wet year (2013) in Central Farm, Belize.

4.1.2.2 Evaporation

To maintain the soil profile moisture content, that will determine the amount of readily available water for crop growth, water loss must be kept to a minimal. However, with daytime heating and different daily atmospheric demand, water is lost from the soil through evaporation, reducing the soil water balance. The removal of moisture from the soil profile through this process as shown in Figure 8, varies throughout the year for the selected years.

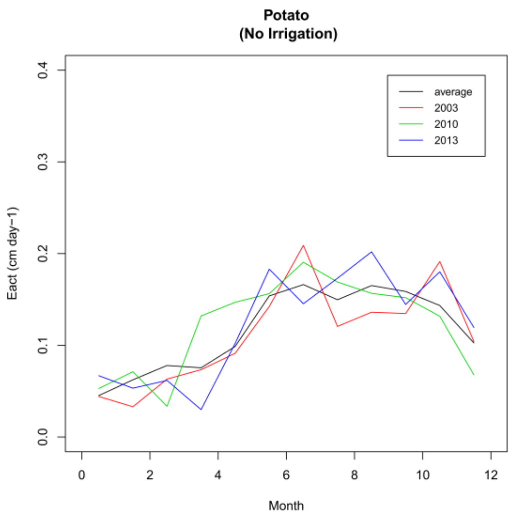

Figure 8. Monthly averages of evaporation for two dry El Niño years (2003, 2010) and a wet year (2013) in Central Farm, Belize.

The evaporative rate was below average for much of 2003 similar to its precipitation amounts seen in Figure 7,and fluctuated from month to month for all years. The reduced evaporative rate seen predominantly in 2003 can be attributed to the dry soil conditions, mainly as a result of lower precipitation, low wind-speed and above optimum temperatures in that year (Rowell, 1994). During the growing season in 2010, the evaporative rate was below average as a result of lower precipitation and high temperatures despite an increase in wind speed. Although 2013 was generally a wet year, it had the lowest evaporative rate in April, coinciding with its lowest monthly precipitation possible due to high relative humidity contrary to 2003, which saw the highest evaporative rate in July.

4.1.2.3 Transpiration

In the absence of crop growth, there is no transpiration as the process only occurs through the leaves via the stomata of crops, as seen in Figure 9. During the DJF months, transpiration rate was above average in 2003 whereas in 2010, December was above average and January and February were below average. In 2013, December and January were above average with February below average.

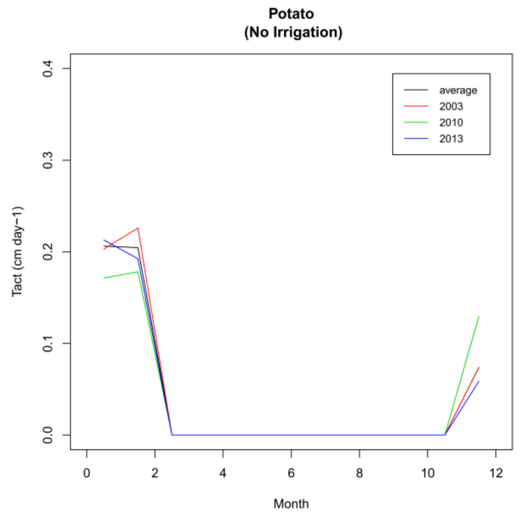

Figure 9. Monthly averages of transpiration for two dry El Niño years (2003, 2010) and a wet year (2013) in Central Farm, Belize.

These results reveal that in 2003, there was sufficient available water for transpiration besides the fact that conditions did not exactly satisfy the humidity period criteria because precipitation and transpiration rate were the same in the DJF water balance averages seen in Figure 6 . In 2010, however, apart from December at the start of the growing season, transpiration rate decreased seen by the below normal averages, indicating that later in the growing season, there could be water stress that would potentially affect key growing stages of the crop. In 2013, the above normal December and January transpiration rates indicate that sufficient water was available for the major developmental stages of the crop, with a decrease in February.

By comparing the input and these two important output soil water balance components, the available soil water that can be utilized in crop growth can be determined by the storage change (STOR). The negative sign in the soil water storage change indicates that the losses were greater than the gains. On average, during the potato crop growing season, there was always a deficit in soil moisture below field capacity with water being extracted from the soil in 2003. December and January STOR were below average, with only February above the negative average storage change. Prior to the start of the growing season in November, there was a positive storage change indicating an excess of soil moisture.

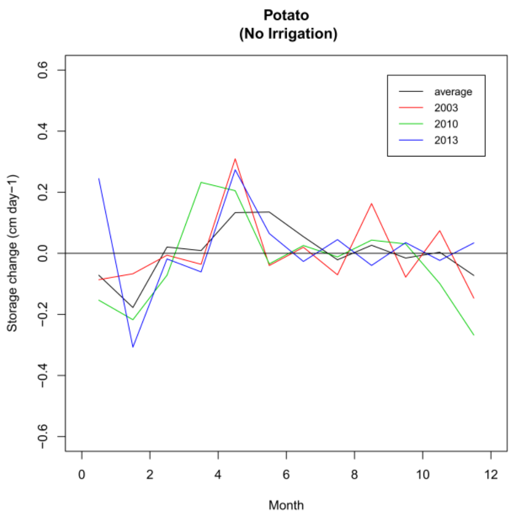

Figure 10. Monthly averages of storage change for two dry El Niño years (2003, 2010) and a wet year (2013) in Central Farm, Belize.

The driest year 2010, showed a storage change was much below the average at the start of the growing season and a deficit remained throughout but reduced later in February. In the wettest year 2013, the storage change was positive and above average in December and January but was way below average in February.

The highest storage change values occurred in May indicating the start of the rainy season for the selected years. It can be concluded that the most notable changes in the inter-annual variability of these primary water balance components occurred in 2010. The precipitation, soil evaporation, transpiration and storage change all indicate that a major deficit in soil moisture occurred in this year alluding to a major decrease in crop yield.

4.1.3 SWAP Yield

4.1.3.1 Rainfed Potato Simulation

The balance between rainfall, evapotranspiration and soil water determines the health (rate and growth development) of the crop. At the beginning of the cropping season, there is the highest demand for water by the crop and ideally, potential and actual evapotranspiration should be equal, however, when the crop is water stressed, the actual evapotranspiration deviates from the potential evapotranspiration.

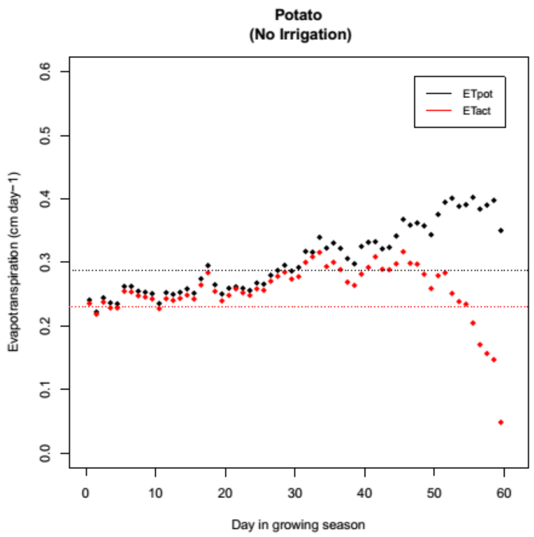

Figure 11. Comparison of potential and actual evapotranspiration during the DJF growing season (no irrigation) of the potato crop in Central Farm, Belize.

This is the case seen on average in the DJF growing season in Central Farm when no irrigation is applied (Figure 11), where horizontal denotes the long term averages over 31 years (1985-2015) and at the start of the season throughout the simulation period, actual evapotranspiration is always slightly lower than the potential evapotranspiration and the difference is further amplified towards the end of the cropping season, where both components diverge from each other. Water stress at critical developmental stages of crop growth can affect the overall yield and quality of the crop (Annandale et al., 2005).

4.1.3.2 Yield

Observed yield data was only available for a fifteen-year period from 2000-2014 therefore a comparison was only possible with simulated yield output for these years (Figure 12).

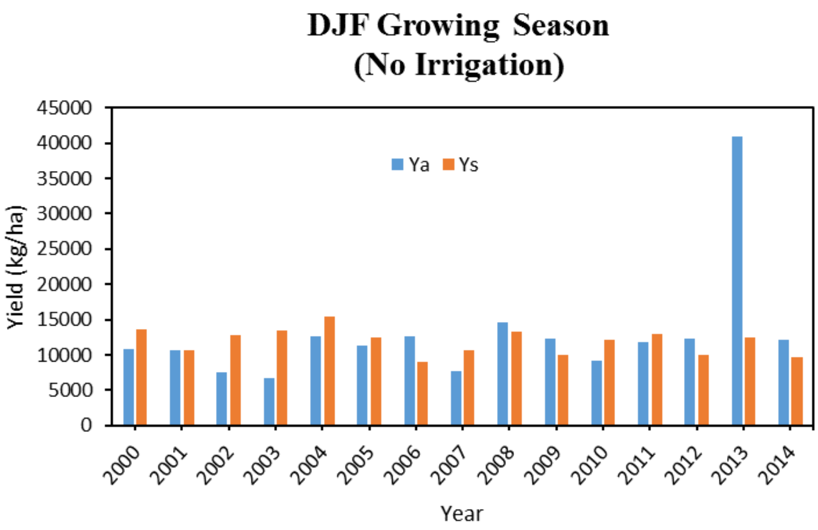

Figure 12. Comparison of observed (Ya) yield vs simulated (Ys) yield for the DJF growing season of potato in Central Farm, Belize

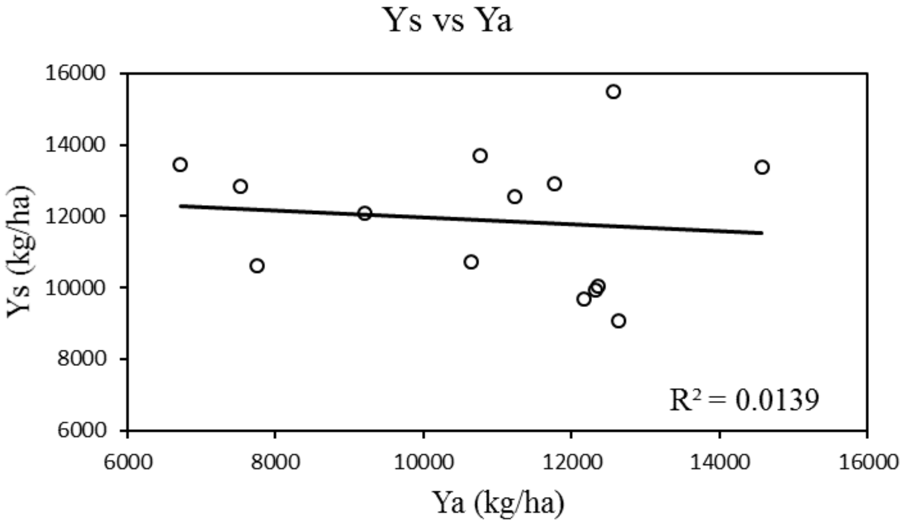

Figure 13. Relationship between simulated yield (Ys) and observed yield (Ya) in Central Farm.

Figure 12 shows that the model overestimated the yield in most years except for 2001 when it was similar to the observed and 2006-9, 2012 and 2014 where it underestimated the yield. A scatter plot of the data presented in Figure 13, together with a linear fit showed that the modelled and observed yield values were poorly correlated yielding an R^2 value of0.0139,where the yield for 2013 was treated as an outlier due to error in the transmission of data and excluded from the analysis. Further statistical analyses were conducted and Table 5 illustrates the results.

Table 5. Statistical Indexes for comparing the modelled and observed yield of Potato

Number of observations	14
Average observed (kg/ha)	10874
Average modelled (kg/ha)	11888
Std dev observed (kg/ha)	2199
Std dev modelled (kg/ha)	1813
Correlation Coefficient	-0.12
ME	6726
RMSE(%)	29.21
CD	1.12
EF	-381
CRM	0.14

The average observed and simulated yield were different and the model averaged higher yield values consistent with its overestimation seen in Figure 12 above. The observed values, however, showed more variability as it had a higher standard deviation compared to the simulated yield. The worst case performance of the model's prediction of yield compared to that of the observed values was given by the ME large value. The Correlation coefficient of -0.12 indicates that there is a negative relationship between the observed and stimulated potato crop yield, but it is weak while the model overestimated the observed yield by 29.2% given by the RMSE value representing large systematic errors. This is an area of the model that has a potential for improvement. The highly negative value of -381 indicates that the averaged observed gives a better estimate the yield than the simulated values.

A 1.12 CD value and a 0.14 CRM value shows that the model and observed values were not identical as the CD value was slightly greater than 1 and the CRM value was greater than 0. Although the statistical analyses indicate that there is not a good fit between the simulated and observed yields, it should be taken into consideration that apart from the input of actual meteorological variables with dubious radiation at some points from the study area, the soil hydraulic parameters, crop parameters, soil profile depth and ground water levels were adapted or estimated and not actual field data but similar to the field site that was used as input into SWAP. In addition to this, the effects of salinity (causing crop water stress) and irrigation (improving yield) were not taken into account for this simulation. Finally, the observed yields obtained from the ministry of agriculture were for the general Cayo district and not necessarily from this specific site as Central Farm is a research area located in the Cayo district and only accounts for a portion of this total yield, leading to a lower simulated yield value than the observed.

Despite the limitations resulting from the methodology and the limited availability of actual field data, the SWAP model has shown that with improvement and input of observed soil and crop parameters in the calibration of the model, it can be adapted for use in the study area, as was seen for the Cuban case by Ruiz and Utset (2003).

4.2 Case Study in Central Farm

A study was done on the growing of potato crop with different irrigation scheduling and a sensitivity analysis on rooting depth and stomatal resistance. The investigations were carried out for the period of 2000 to 2014, where fixed weekly irrigation amounts and the six scheduling irrigation criteria were applied as outlined in sections 3.3.1and 3.3.2.

4.2.1 Irrigation

Irrigation scheduling is an important managerial practice to improve water use efficiency and conserve water and energy in areas prone to frequent drought events and high pumping costs (Camargo, 1993). By altering the upper boundary conditions through irrigation, soil moisture, transpiration and yield were affected. In Table 6, the results show the years and irrigation depths, where a deficit in the soil moisture was detected during the growing season. Here, different irrigation scheduling requirements were prescribed where RAW is the readily available water, TAW is the total available water, WA is the available water, FWI Rzone FC is the fixed weekly irrigation in the root zone to field capacity along with daily stress and pressure head.

Table 6. Year and Irrigation Amount (AMT) for different scheduling irrigation schemes in the DJF growing season of the potato crop (calculated using SWAP model run, July,2016)

	Daily Stress		Depletion of RAW		Depletion of TAW		Depletion of WA		Pressure head		FWI Rzone to FC	
	Year	AMT(cm)	Year	AMT(cm)	Year	AMT(cm)	Year	AMT(cm)	Year	AMT(cm)	Year	AMT(cm)
1	2002	5.5	2000	8.7	2000	8.1	2002	5.0	2002	5.5	2000	2.8
2	2004	5.3	2001	10.0	2001	9.7	2004	5.1	2004	5.3	2001	3.7
3	2010	10.7	2002	14.4	2002	14.0	2008	5.1	2010	11.0	2002	8.8
4	2014	5.4	2003	8.8	2003	8.8	2010	10.5	2014	5.4	2003	3.2
5			2004	15.7	2004	15.2	2014	5.0			2004	9.6
6			2005	8.9	2005	8.8					2005	3.5
7			2006	6.6	2006	6.0					2006	4.4
8			2007	9.8	2007	9.5					2007	4.5
9			2008	12.2	2008	11.7					2008	4.2
10			2009	9.8	2009	9.5					2009	5.2
11			2010	18.4	2010	18.5					2010	14.7
12			2011	11.3	2011	10.9					2011	6.2
13			2012	9.2	2012	8.8					2012	6.8
14			2013	6.7	2013	6.4					2013	2.9
15			2014	12.9	2014	12.3					2014	9.9

The depletion of readily available water, total available water and fixed weekly irrigation in the root zone back to field capacity scheduling irrigation criteria were the most sensitive to water stress as Table 6 indicates that all investigated growing seasons required some depth of irrigation. On the other hand, only 2002, 2004, 2010, and 2014 required irrigation based on the daily stress and pressure head criteria with 2008 included by the depletion of available water criteria. All scheduled irrigation criteria detected that water stress occurred and hence resulted in irrigation in 2010, which was an El Niño year where the soil water storage fell below the critical value prescribed by each method, as the largest quantity of irrigation water was applied in this year. In the other two years of interest, 2003 (dry) and 2013 (wet), 2003's water stress was not significant during the growing season as none of the irrigation scheduling methods caused the model to supply irrigation during this period, while in 2013, water stress was not significant during the growing season as only three of the six methods applied one of the lowest irrigation depths, consistent with the overall year being considerably wet.

4.2.1.1 Water Balance and Irrigation Scheduling

The water balance components for the 2003, 2010 and 2013 potato crop are shown in Table 7, Table 8 and Table 9for all six irrigation scheduling criteria. For the wettest irrigation scheduling criteria, the depletion of RAW in 2003, the total water used for crop transpiration was 13.9 cm, for soil evaporation 5.6 cm, for bottom flux -14.4 cm and for runoff 1.3 cm, while 31.5 cm was imputed by precipitation and irrigation. The water losses were replaced by irrigation resulting in a soil water change of -3.7cm. Water loss by evapotranspiration was mainly due to transpiration (70%) while soil evaporation was 30%.

For the driest irrigation scheduling criteria, depletion of available water, in 2003, the total water used for crop transpiration was 14.7 cm, for soil evaporation 5.7 cm, for bottom flux -10.8 cm and for runoff 1.4 cm, while 22.7 cm was imputed by precipitation. There was no irrigation applied resulting in a larger soil water change of -10.0 cm yielding results similar to the rainfed condition with a slightly higher soil storage loss. Water loss by evapotranspiration was mainly due to transpiration (74%) while soil evaporation was 26%.

Table 7. Total water balance values, in cm, for the DJF growing season, in relation to the components Precipitation (Prec), Irrigation (I), Transpiration(Tact), Evaporation (Eact), Evapotranspiration (ETact), Runoff (RO), Bottom Flux (BF) and Storage Change (STOR) in 2003.

	Irrigation Schedule						
Component	Daily Stress	Depletion of RAW	Depletion of TAW	Depletion of WA	Pressure head	FWI Rzone to FC	No Irrigation
Prec+I	22.7	31.5	31.5	22.7	22.7	25.9	22.7
Eact	5.7	5.6	5.9	5.7	5.7	5.7	5.7
Tact	14.7	13.9	13.9	14.7	14.7	14.6	14.7
ETact	20.5	19.5	19.8	20.5	20.5	20.3	20.5
RO	1.4	1.3	1.3	1.4	1.4	1.4	1.4
BF	-10.5	-14.4	-14.0	-10.8	-10.6	-10.8	-10.5
STOR	-9.7	-3.7	-3.7	-10.0	-9.7	-6.7	-9.7

For wettest irrigation scheduling criteria, the depletion of TAW and RAW, in 2010, had similar values for the total water used for crop transpiration was 18.2 and 18.1 cm, for soil evaporation 4.9 and 4.4 cm, for bottom flux -12.2 and -12.4 cm and for runoff 0.5 and 0.5 cm respectively, while 35.3 cm was imputed by precipitation and irrigation. The water losses were replaced by irrigation resulting in a soil water change of -0.4 and -0.3 cm respectively, indicating that higher irrigation amounts led to more gains in the soil water storage. Water loss by evapotranspiration was mainly due to transpiration (79%) while soil evaporation was around 30%.

Table 8. Total water balance values, in cm, for the DJF growing season, in relation to the components Precipitation (Prec), Irrigation (I), Transpiration(Tact), Evaporation (Eact), Evapotranspiration (ETact), Runoff (RO), Bottom Flux (BF) and Storage Change (STOR) in 2010.

	Irrigation Schedule						
Component	Daily Stress	Depletion of RAW	Depletion of TAW	Depletion of WA	Pressure head	FWI Rzone to FC	No Irrigation
Prec+I	27.6	35.3	35.3	27.4	27.8	31.6	16.9
Eact	4.4	4.5	4.9	4.6	4.8	5.4	4.4
Tact	17.9	18.1	18.2	19.9	19.9	19.7	17.9
ETact	22.4	22.6	23.1	24.5	24.7	25.2	22.4
RO	0.6	0.5	0.5	0.6	0.6	0.5	0.6
BF	-9.8	-12.4	-12.2	-9.8	-9.7	-10.2	-9.8
STOR	-5.2	-0.3	-0.4	-7.6	-7.2	-4.3	-15.9

For the driest irrigation scheduling criteria, depletion of available water, in 2010, the total water used for crop transpiration was 19.9 cm, for soil evaporation 4.6 cm, for bottom flux -9.8 cm and for runoff 0.6 cm, while 27.4 cm was imputed by precipitation and irrigation. Precipitation total was only 16.8 cm when no irrigation was applied. The resulting soil water change was -7.6 cm while in the rainfed condition it was -15.9 cm indicating a greater loss. Water loss by evapotranspiration was mainly due to transpiration (81%) while soil evaporation was 19% with slightly lower values in the rainfed condition.

On the other hand, with the wettest scheduling criteria, the depletion of RAW in 2013, the change in soil water content was +2.0 cm, including 13.5 cm of crop transpiration, 8 cm of soil evaporation, 1.4 cm of runoff, -34.1 cm of bottom flux, and 59 cm of rainfall and irrigation. A soil water change of -4.1 was recorded for no irrigation and the daily stress and depletion of WA criteria in the driest applications.

Table 9. Total water balance values, in cm, for the DJF growing season, in relation to the components Precipitation (Prec), Irrigation (I), Transpiration(Tact), Evaporation (Eact), Evapotranspiration (ETact), Runoff (RO), Bottom Flux (BF) and Storage Change (STOR) in 2013.

	Irrigation Schedule						
Component	**Daily Stress**	**Depletion of RAW**	**Depletion of TAW**	**Depletion of WA**	**Pressure head**	**FWI Rzone to FC**	**No Irrigation**
Prec+I	52.3	59.0	58.7	52.3	52.3	55.2	52.3
Eact	7.3	8.0	8.2	7.2	7.2	7.6	7.3
Tact	13.7	13.5	13.5	13.6	13.6	13.6	13.7
ETact	20.9	21.4	21.7	20.9	20.9	21.3	20.9
RO	1.4	1.4	1.4	1.4	1.4	1.4	1.4
BF	-34.0	-34.1	-34.1	-34.0	-32.8	-33.0	-34.0
STOR	-4.1	2.0	1.6	-4.1	-2.9	-0.6	-4.1

Lastly, as irrigation affected total transpiration, it also influenced the daily transpiration rates during the growing season where irrigation eliminated water stress in the crop. In Figure 14, a general trend in the transpiration rate was observed in all irrigation schedules and the rain-fed condition but the transpiration rate from the depletion of total available water (DTaw) was lower than the other methods throughout the growing season. Around day 35, pressure head schedule (Phead) had the highest transpiration rates compared to the other schedules as the highest amount of water (not shown) was applied to bring the soil water back to field capacity. As the transpiration rate started to decrease towards the end of the growing season with a decrease in leaf area, all irrigation schedules displayed a similar trend.

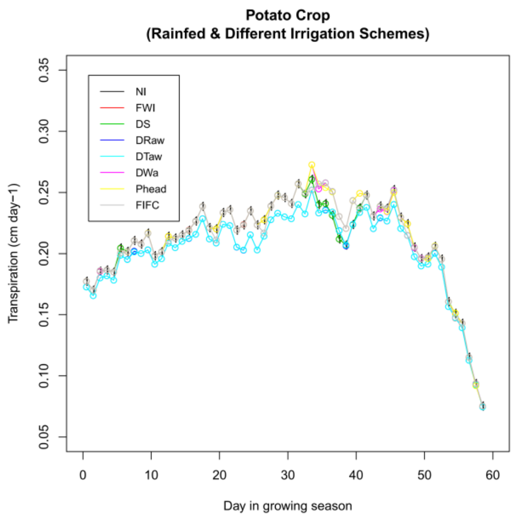

Figure 14. Comparison of daily transpiration during the DJF potato growing season in Central Farm, Belize with no irrigation (NI) and different irrigation schemes simulated by SWAP July, 2016.

In general, the results show that irrigation can be used to replenished water loss during dry conditions as in 2010, resulting in a higher transpiration total as more becomes water available in the root zone, coupled with a high atmospheric demand while in wet conditions as in 2013, less irrigation is required with more gains to the soil moisture with a positive storage change. Transpiration amounts are also reduced due to high relative humidity as a result of a moist atmosphere, decreasing the atmospheric demand. Figure 14 revealed that there is no significant difference in the transpiration rate between no irrigation and the different irrigation scheduling criteria.

4.2.2 Sensitivity Analysis of Stomatal Resistance and Rooting Depth

Minimal stomatal resistance and maximum rooting depth affect transpiration rate as water is only able to be lost by transpiration if it is available. Figure 15 shows the relationship between daily transpiration rate during the potato growing season with stomatal resistance and rooting depth displaying a similar pattern. Firstly, the stomatal resistance of 25 s/m (SR25), 50 s/m (SR50) and 100 s/m (SR100) all showed a similar trend with an overall steady increase in daily transpiration at the beginning of the growing season as the leaf area increased, adding more surface area for water loss by leaves. As stomatal resistance decreased, the transpiration rate increased as SR25 showed the highest transpiration rate. Daily fluctuations were observed when there was a deficit in the available soil moisture and a high atmospheric demand causing a decrease in the transpiration rate. The most notable decrease occurred around day 40 indicating that the crop underwent significant water stress during this period. The highest transpiration rate occurred after this point with the largest leaf area and decreased drastically as the crop started to shed its leaves reducing transpiration rate.

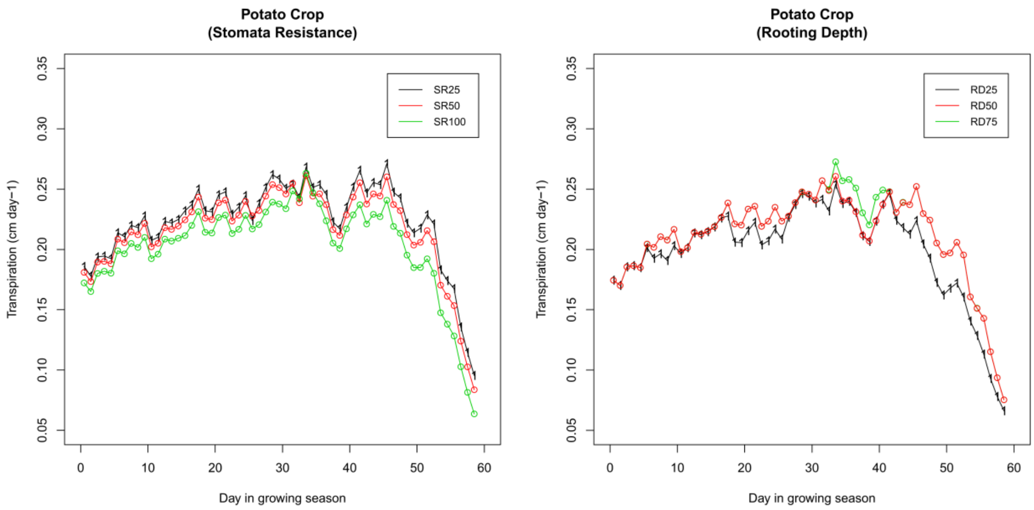

Figure 15. Comparison of daily transpiration during the DJF potato growing season in Central Farm, Belize with stomatal resistance and rooting depth simulated by SWAP July, 2016.

Secondly, potato is a shallow rooted crop and varying the rooting depth to 25cm (RD25), 50cm (RD50) and 75cm (RD75 also affected the transpiration rate. At the beginning of the growing season, all three depths had the same transpiration rate until between day 6-11 where the transpiration rate at rooting depth RD25 decreased indicating a decrease in soil moisture to meet the evaporative demand while RD50 and RD75 transpiration rate continued to increase. Between days 18-30, although daily fluctuations in transpiration occurred, the rate for both RD50 and RD75 was the same but RD25 was lower indicating less available soil moisture. The highest transpiration rate occurred at day 35 for RD75 and after day 45 to the end of the growing season, the transpiration rate started to decline as the crop began to shed its leaves and the soil moisture decreased. It was clear that by increasing the rooting depth, the plant has access to more water by tapping into ground water resources and can minimize water stress indicated by higher transpiration rates.

Overall, it can be concluded that increasing stomatal resistance and decreasing rooting depth decreased the transpiration rate, reducing the flow of water through the plant, which can have an effect on the overall yield.

4.2.3 Yield

The alteration of stomatal resistance, rooting depth and varying irrigation scheduling all affected the simulated yield in 2010 but yield was also affected in 2002 and 2004 for RD25, two years where the second and third highest irrigation depths were applied by all irrigation schedules shown in Table 6. Table 10shows these changes.

Table 10. Changes in simulated yield in 2010 by varying the stomatal resistance, rooting depth and irrigation parameters.

Year	**2002**	**2004**	**2010**
Parameter	**Yield**	**Yield**	**Yield**
Stomata1 Resistance	**(kg/ha)**	**(kg/ha)**	**(kg/ha)**
25	-	-	11470
50	-	-	11743
100	-	-	12575
Rooting depth			
25	12291	13143	8815
50	-	-	12067
75	-	-	13925
Irrigation			
Daily Stress	-	-	12067
Dtaw	-	-	13925

Significant changes in yield were observed in 2010 for all parameters and only in 2002 and 2004 for RD25. The yield was increased by increasing the stomatal resistance as it caused a reduction in transpiration as was seen in Figure 15 as the stomatal opening decreased to conserve water under water stress that was used in the crop growth. Yield also increased by increasing the rooting depth as the plant was able to access water from depth where there is more available soil moisture compared to at 25cm near the surface, where less water was available due to the fact that water is also able to evaporate from the soil surface. In 2002 and 2004, the yield values observed at RD25 was significantly lower with no irrigation applied compared to RD50 and RD75. Change in yield was only observed in the daily stress criteria in 2010 when irrigation was prescribed, as this value was lower than all other irrigation schedules, all of which resulted the same yield value as the DTaw scheme.

4.3 Drought Indices

4.3.1 Comparison of ETDI and SMDI

ETDI was calculated using potential and actual evapotranspiration data and SMDI using soil moisture content at 50 cm depth for 2000 to 2014, generated from SWAP model outputs and their comparison yields the result shown in Figure 16.

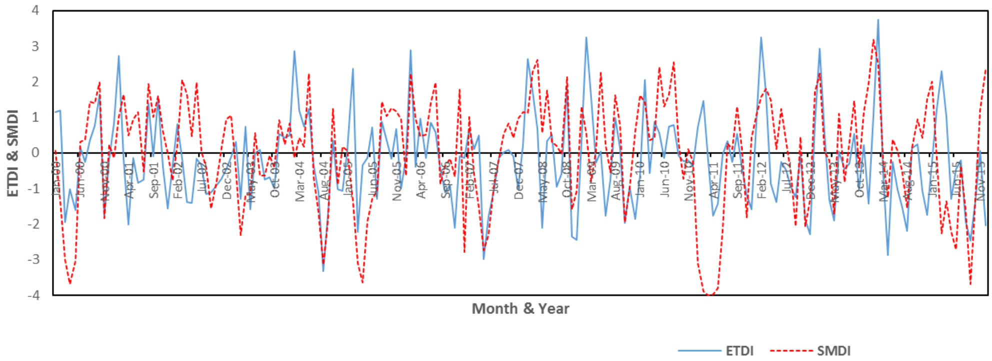

Figure 16. Comparison of monthly ETDI and SMDI values for Central Farm, Belize (2000-2014).

In Figure 16, positive values indicate wetness and negative values indicate dryness. Both indices mostly show a similar trend in peaks and drops however, their amplitudes as well as certain instances when depicting dry conditions, varied. ETDI reached more than -3 in August 2004 and SMDI reached -4 in December 2010 indicating extreme dryness. The wettest condition was detected by both indices in 2013.

A scatter plot of the data presented in Figure 16, together with a linear fit showed that ETDI and SMDI were marginally correlated yielding an R^2 value of 0.2117.

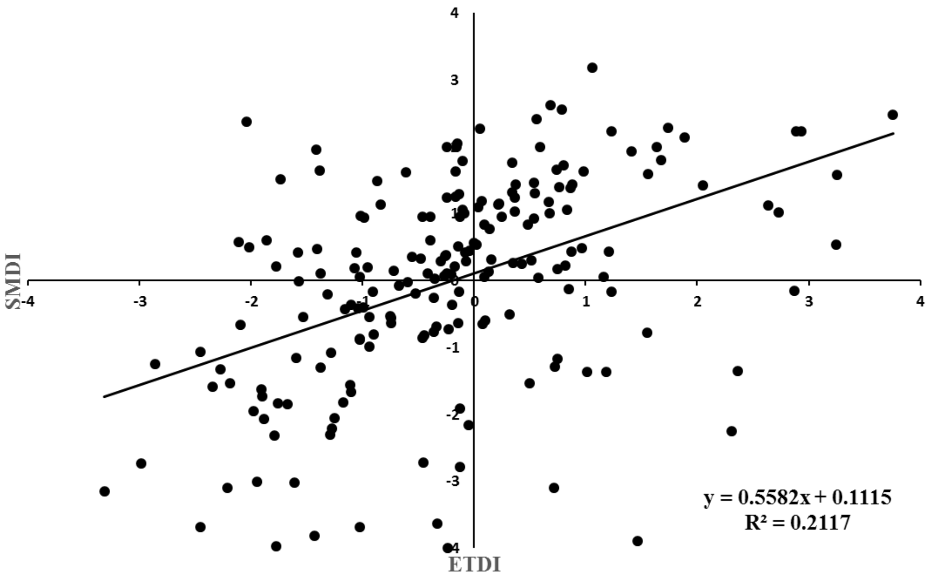

Figure 17. Relationship between ETDI and SMDI for Central Farm, Belize (2000-2014).

Further statistical tests of the two drought indices were conducted and Table 11 illustrates the results:

Table 11. Statistical Analysis of ETDI and SMDI (2000-2014).

Index	Median	Mean	Max	Min	Std dev.	No. of times > 3	No. of times < -1	No. of times < -2	No. of times < -3
ETDI	-0.19	-0.20	3.75	-3.32	1.27	3	54	13	1
SMDI	0.21	0.00	3.18	-3.99	1.54	1	45	22	12

From these results, SMDI detected drier conditions than ETDI with minimum values of -3.99 while ETDI had a minimum of -3.32, however, ETDI detected wetter condition with a maximum value of 3.75 compared to 3.18 for SMDI. ETDI was more sensitive to dry conditions as it had a higher frequency of values <-1 with 54 but SMDI identified more extreme dryness with a frequency of 22 for values <-2.

During the potato growing seasons of 2003 (dry), 2010 (dry) and 2013 (wet), both indices were compared and the results displayed in Figure 18:

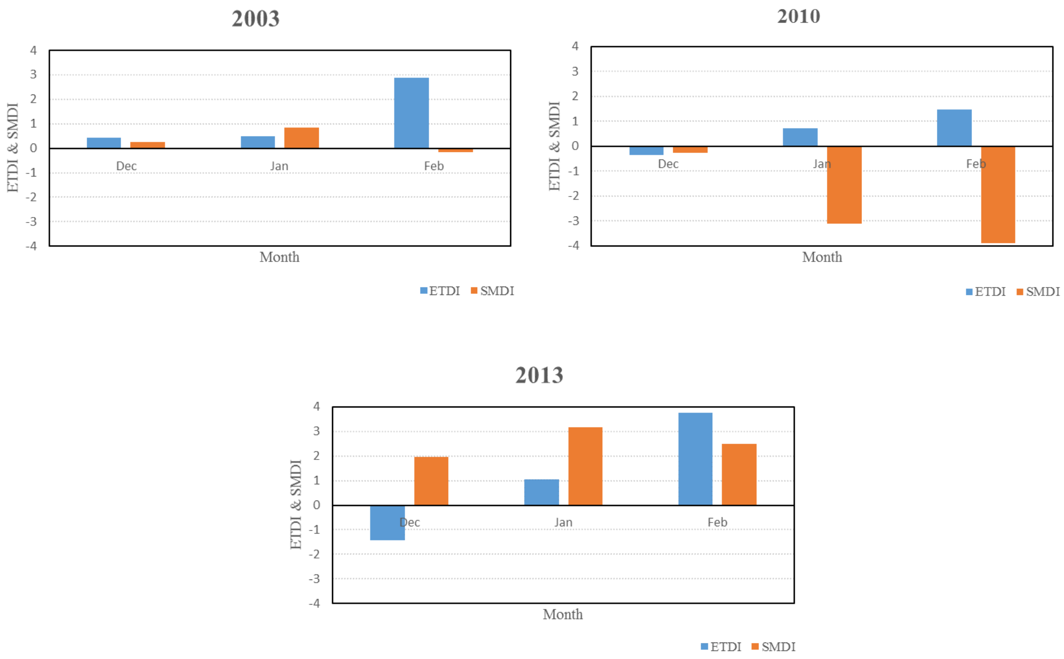

Figure 18. Comparison of monthly ETDI and SMDI values during the potato growing season for 2003, 2010 and 2013 for Central Farm, Belize.

In the 2003 growing season, both ETDI and SMDI detected wet conditions though not extreme except for February by ETDI while SMDI detected slightly dry conditions. In the 2010 season, SMDI detected dryness in all three months with extreme values in January and February while ETDI detected wet conditions except for December. Lastly in the 2013 season, all SMDI values displayed extreme dryness while ETDI detected wet conditions January and February but dry in December.

Therefore, with the results presented, both indices performed well when conditions were not extremely dry or when it was wet but were not in agreement when conditions were extremely dry as in 2010 with SMDI consistently detecting dryness.

Chapter 5 – Conclusion and Recommendation

5.1 Conclusion

The aim of the study was to determine the effect of drought on the water balance and yield of the potato crop in Belize. The study was conducted for the period 1985 to 2015 with emphasis being place between 2000 and 2014, using the input of daily meteorological variables and generic potato crop parameters prescribed by the SWAP model. Intra- and inter-annual variability of the water balance components and their effect on yield were investigated and well as SWAP model’s sensitivity in predicting yield. A case study was also conducted on the area using different irrigation scheduling criteria along with a sensitivity analysis on stomatal resistance and rooting depth to determine their effect on transpiration rate and yield. Two agricultural drought indices were used to test the occurrence and severity of drought in the study area. The results yielded the following answers to the research questions.

1. What is the intra- and inter-annual variability in the water balance and related yield of the potato crop grown in Belize, as derived from the SWAP model?

   It was found that the simulated water balance components varied seasonally with the wet season yielding higher precipitation, soil evaporation and soil moisture gains, whilst a reduction in precipitation, soil evaporation and soil storage change was seen in the dry season with an increase in water loss by transpiration. During the potato growing season, the water balance produced a deficit in soil moisture and dry conditions in 2010, which was later confirmed by a reduction in simulated yield when no irrigation was applied.

Furthermore, during the investigated dry years of 2003 and 2010, the water balance components yielded below average values with the exception of above average precipitation and a surge of moisture in November of 2003, prior to the start of the growing season. As a result, no significant loss of the crop nor reduction in soil moisture was detected by SWAP in 2003, while significant losses were observed in 2010. When experiencing excessive rainfall as in 2013, above average values were observed for the water balance components with positive storage gains and no loss of crop.

2. What is the sensitivity of the SWAP model outputs to key crop parameters?

   In general, SWAP overestimated the yield for most years and was poorly correlated with the observed yield. Increasing the stomatal resistance led to a reduction in transpiration rate over the growing season while transpiration increased with increasing rooting depth. Higher stomatal resistance and deeper rooting depth were found to increase the simulated yield significantly but only in 2010, while yield remained unchanged for the remaining years. The shallow rooting depth of 25 cm was the most sensitive to dry conditions as yield was reduced in 2002, 2004 and 2010.

3. Can SWAP be used to improve irrigation planning in Belize?

   Several fixed and scheduling irrigation criteria prescribed in SWAP were applied and all methods consistently depicted 2010 as a dry year, requiring the largest irrigation depths seen by the water balance components in section 4.2.1.1. In rain-fed conditions, the simulated yield in this year was low and increased when irrigation was applied. The results show the SWAP model's ability to detect soil water deficit and apply the necessary water amount to account for losses in soil moisture. As a result, SWAP has the potential to be utilized as an irrigation planning tool in Belize, as it was able to detect a deficit in soil moisture, apply sufficient irrigation depths and increase yield.

4. What is the relationship between agricultural drought indices in Belize?

   ETDI and SMDI was found to be marginally correlated with an R^2 value of 0.2117, however, both indices displayed a similar trend in peaks and drop during wetting and drying events. The SMDI was found to be most sensitive to soil moisture deficit and was able to detect both drying and wetting events consistent with what was observed in the 2010 (dry) and 2013 (wet) growing seasons.

5. What is the occurrence and severity of drought events and how do these affect crop yield?

   Both ETDI and SMDI detected that during the investigated period of 2000-2014, drought conditions did occur with a high frequency of months with indexes < -1 and < -2, with SMDI having a higher frequency of extreme dry conditions (12 months) having values < -3, while ETDI only detected 1 occurrence. The maximum occurrence of an index >3 was only 3 months, indicating that extreme wet events were not as prevalent as the dry extremes during the 2000-2014 period.

   Despite these findings, yields were only significantly affected in 2010, indicating that there seems to be little impact of drought during this period.

5.2 Limitations

- There is a limited amount of agrometeorological observing stations in the area where the observed yield data was collected and the meteorological variables were from an adjacent station.
- Accurate validation of the model was not possible because there are no ground measurements of soil moisture content, soil hydraulic parameters and ground water levels being recorded in the area.
- The SWAP potato crop file used was generic and not specific to the La Rouge Potato grown in Central Farm.
- The quality of input meteorological variables such as radiation could have affected the yield results as a relatively high percentage was missing and calculated with max and min temperatures.
- The observed yields used to validate the model's performance were not specific to Central Farm but for the Cayo district.
- Investigations were carried out at one specific site but the impact of drought in Belize varies depending on location.
- The selection of drought prone crops to be investigated were limited by the availability of meteorological and agricultural data in the cropping areas of Belize.

5.3 Recommendation

- Good field measurements of soil moisture, ground water level and soil physical parameters will be useful in the calibration of the model for the area in future work.
- The is a need for the development of a crop specific agricultural network for the measurement and collection of soil moisture, evapotranspiration, leaf area, rooting depth, temperature sums and other data during the growing seasons to improve the efficiency of the model.
- Access to site specific observed yield data can be used to improve the correlation between the simulated and observed yield in the sensitivity analysis.
- Detailed customization of the SWAP crop file for the La Rouge potato species and other crops in tropical regions is required for future work.
- Improvement on communication and data and information sharing between the relevant stakeholders is a must to aid in the calibration of the SWAP model for Belize and other tropical areas, in order to capitalize on its ability to simulate crop growth, schedule irrigation and make use of other water and agriculturally related management techniques.

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Appendix 1: List of Appended Equations

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right)$$ [16]

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right)$$ [17]

$$\omega_s = \arccos\,[-\tan(\varphi)\tan(\delta)]$$ [18]

$$\frac{24(60)}{\pi}Gsc = 37.59 \text{ MJ m}^{-2}\text{ day}^{-1}$$ [19]

$$ME = \max\left|(P_i - O_i)\right|_{i=1}^{n}$$ [20]

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2\right)^{1/2}\frac{100}{\overline{O}}$$ [21]

$$CD = \frac{\sum_{i=1}^{N}(O_i - \overline{O})^2}{\sum_{i=1}^{N}(P_i - \overline{O})^2}$$ [22]

$$EF = \frac{\sum_{i=1}^{N}(O_i - \bar{O})^2 - \sum_{i=1}^{N}(P_i - O)^2}{\sum_{i=1}^{N} O_i} \qquad [23]$$

$$CRM = \frac{\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} O_i} \qquad [24]$$